Review Paper:

Protein-Based Nanostructures: A Promising Trend in Food Industry

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Abstract
Nanotechnology has shown remarkable progressive innovations in the various fields of biology and biochemistry. Worldwide applications of nanotechnology can be best described in the areas of biomedical applications, drug delivery systems, biosensing and biocatalysis, vaccine designing and development etc. Nanotechnology with its recent developments and advancements brings about a huge impact on the food sector.

Proteins due to their biocompatibility and biodegradability, are widely used as an essential part of food-grade nanomaterials. Protein-based nanostructures made from different kinds of proteins provide new options for nanotechnology in the food industry through their innovative range of food applications for processing, packaging, the shelf life of foods, quality control and enhancement of nutritional value. This study reviews the highlights of the recent developments of protein-based nanostructures such as nanocapsules, nanoemulsions, nanocoatings, nanohydrogels and nanosensors in the food industry.

Keywords: Nanotechnology, Proteins, Protein-based nanostructures, Food applications, Nanosensors, Gel and Hydrogel, Nanocoatings, Self-assembled proteins.

Introduction
Nanotechnology has emerged as a key technology in the 21st century. Certain industries related to electronics, aerospace and pharmaceuticals have already started the implication of nanoscale materials in the manufacturing of commercial products. Exploration of nanotechnology applications has just emerged in the food and other industries with great potential[15,25,67]. Foods are complex biological systems governed by some basic mechanisms and principles; food undergoes a series of changes during postharvest and processing including its biochemical and biological makeup. Developments in the field of nanotechnology can influence food industries in various fields of biology and biochemistry. The various aspects related to molecular synthesis and food safety have been greatly affected by the systems having structural features in the nano range.

Nanotechnology in the food industry: The innovative application of nanotechnology in various dimensions of food items has created a revolution in food industries. Most of the work has been done in the enhancement of food quality, modification of food structures and textures; bioactive fortification, controlled release of bioactive compounds, intelligent food packaging systems, food formulation, food storage and improvement in the shelf life of the products[37,47]. The first nano-application in the food industry was an antimicrobial peptide encapsulated starch nano colloid that was used to stop the antimicrobial degradation of packaged food products. If microorganisms grow on packaged food the coating of starch on the nano colloid will be broken by the microorganisms resulting in the release and therapeutic action of antimicrobial agents.

Consequently, the introduction of nanotechnology as nanofood appeared in the food sector. The latest applications of nanotechnology in the food sector include encapsulation and delivery to targeted sites, enhancement of the flavor, antibacterial nanoparticles introduction into food, shelf life enhancement, sensing of contamination, improved food packaging and food storage. This development has given new opportunities for nanotechnology as nano-capsules, nano-carriers, nano-tubes, nano-sensors and nano-packaging in the food industries[18,77].

Nano-packaging, a new-generation technology in food packaging represents an extensive alternative to traditional packaging. The incorporation of nanomaterials offers mechanical strength and provides a barrier against moisture, volatile components (e.g. flavors) and gases. Some of the nano colloidal systems (e.g. nano clay, SiO_2-NPs, TiO_2-NPs), having reduced permeability, improved heat resistance and mechanical properties block UV radiation thereby ensuring better food prevention. The shelf life of oxygen-sensitive foods can be enhanced by nano clay-incorporated packaging that acts as a barrier between atmospheric gases/moisture and packed food material.

To increase the shelf life, active packing has attracted much attention that involves the incorporation of nanoparticles (MgO-NPs, ZnO-NPs, AgNPs, TiO_2-NPs) with antioxidant and antibacterial properties into the packaging material[57]. Nanosensor incorporation into food packaging for tracking and detection of any unwanted physicochemical changes in food during transportation and storage has evolved as intelligent packaging[43,50].

Various nanosensors and nanotracers conjugated with nanomaterials (e.g. Au nanoparticles, Pd nanoparticles, Si nanorods, magnetic beads, quantum dots, carbon nanotubes,

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immune-magnetic liposomes and aptamer conjugated gold) are efficient in the detection of degradants that can significantly affect the food quality[43,50]. Biosensors are a kind of measurement device which are used to measure the content of alcohols and acids in fermented foods. These biosensors contain a biological receptor that works as a target recognition entity and a transducer that translates specific biological recognition into an appropriate signal by electrochemical, optical and mechanical processes. These devices are generally used in quality control processes in the food sector.

Most of the reported biosensors are used to detect natural toxins and pathogens, toxic metals, antibiotics, mycotoxins, residual pesticides, vitamins B complex, fatty acids, bisphenol A etc. The limitations of laborious and costly laboratory techniques can be overcome by the on-spot use of biosensors[43]. Apart from inorganic nanoparticles, organic nanoparticles are widely used in the food sector. Owing to the composition of lipids, proteins or carbohydrates, these nanoparticles are less toxic and are digested completely within the human gastrointestinal tract, thus are non-bio persistent[27]. Lipid nanoparticles are generally used as beverage emulsions and colloidal delivery systems[68].

Casein micelles, the common protein nanoparticles found in foods have little toxicity concern[33]. Recently, other types of protein nanoparticles are being developed to create encapsulated delivery systems and for bioactive agent delivery similar to that of lipid nanoparticles[28]. Carbohydrate nanoparticles are formed of digestible/indigestible polysaccharides[51]. Nanoparticles from carbohydrates are prepared by breaking down starch granules; chitosan/cellulose fibrils are typical for encapsulated delivery systems. Complex nanoparticles with the combination of lipids; proteins and carbohydrates are also being fabricated[42]. Overall the use of organic nanoparticles depends upon their sensitivity toward enzyme hydrolysis. Fig. 1 represents the applications of protein nanoparticles in the food industry.

Numerous prospective applications of nanotechnology in the food sector have emerged with highly promising improvements in the quality and safety of food products. These include active and intelligent packaging, nano-encapsulation, nano-bio sensors, nano-composites etc. The estimated world market for nano foods is rapidly growing and is estimated at $ 20 billion in 2010 and 1 trillion by 2015 for the entire nanotechnology production.

Protein-based nanostructures

Role of Protein-based nanostructures: Protein, renewable natural macromolecules can be easily obtained from animal and plant origin. Furthermore, protein-based nanomaterials are biocompatible, easily processed and biodegradable[55]. Various protein nanoparticles with different types of proteins exhibiting a wide range of applications have been reported[65].

Silk fibroin is the most abundantly used natural polymer for the efficient delivery of bioactive molecules and hydrophilic/hydrophobic drugs[35]. The silk protein in combination with biopolymers like insulin, chitosan, albumin and other synthetic polymers has been fabricated for increased efficacy in drug delivery[21,80]. Another source of protein is keratin, a fibrous structural protein derived from quills, feathers, scales and hairs of birds, reptiles and mammals that have been used for controlled release due to their response to changes in pH and release of drugs[16].

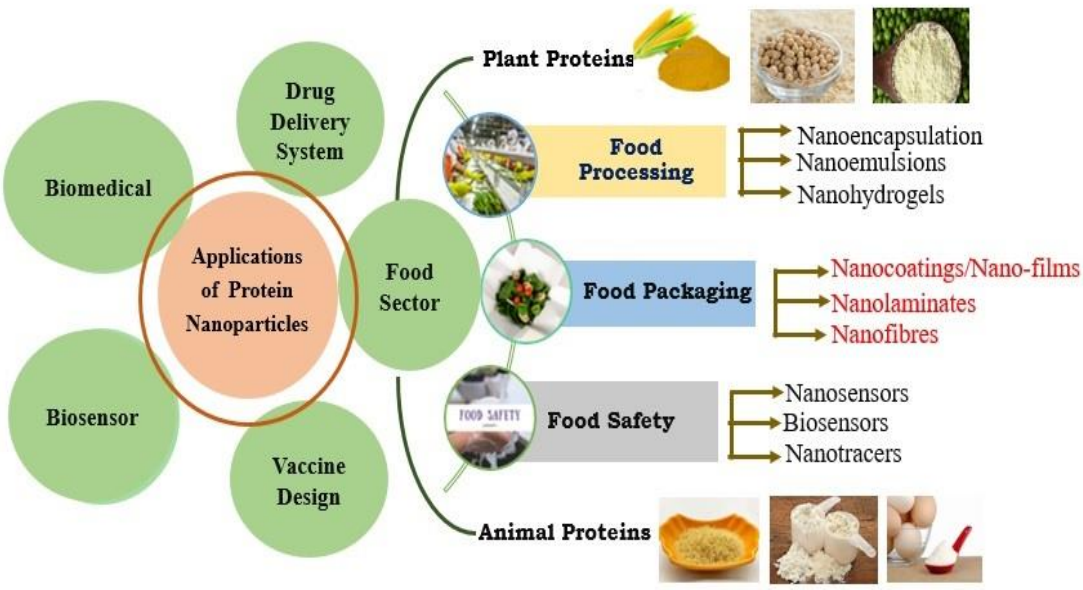

Figure 1: Schematic representation of applications of protein nanoparticles in the food industry

Collagen, a fibrous protein in connective tissues like skin, tendons and ligaments in the human body has been used in the delivery of drugs like theophylline, retinol, lidocaine etc. due to its biocompatibility and low antigenicity[44]. Gelatin, derived commonly from the collagen of animal body parts is used extensively as a carrier for the delivery of genes and anticancer drug[86]. Elastin, an extracellular matrix protein, found application in the effective delivery of cytokines, anticancer therapeutics and genes[53]. Applications of animal-based protein nanostructures are given in table 1.

Proteins from a plant source like zein obtained from corn cell endosperm exhibit hydrophobic properties, due to this they can be used as a suitable nanocarrier for the delivery and controlled release of vitamins, vaccines, other proteins and α-tocopherol[34,52]. Due to the easy digestion of soybean protein, it has been used as protein-based edible coatings. Hydrogels, scaffolds and films of soy protein have wide applications in tissue engineering and transdermal drug delivery[70]. Applications of plant-based protein nanostructures are given in table 2.

Table 1
Animal-based proteins nanostructures and their applications

Nanostructures	Examples With Compositions	Applications
Nanoencapsulation	Self-assembled Casein micelles are natural nanocapsules used for loading of minerals and nutrients e.g. Vitamin D2.	This tendency of casein micelles is used for the enrichment of food products and the best service in delivering hydrophobic Nutraceuticals[61].
	Cross-linking of Collagen with Keratin	Improvement is observed in the mechanical properties and thermal resistance of film based on collagen[81].
Nanoemulsions	Self-assembly of Whey Protein Isolate (WPI) with almond gum was achieved to give an oil-water emulsion with Thymol.	This system was used to encapsulate thymol and resulted in the enhanced stability of the emulsion[60].
Nanocoatings/ Nanofilms	Gelatin-based films are incorporated with many antimicrobial agents such as oregano essential oils and citric acid.	This incorporation shows antimicrobial properties by inhibiting the growth of microorganisms in food packaging[23,75].
	Edible coatings with active films based on Whey protein after incorporation with oregano and essential oils.	These coatings enhance the film's functionality by providing good matrices for antimicrobial agents to release active compounds against the growth of microorganisms[62].
	Edible films of calcium caseinate and whey protein isolate with carboxymethyl cellulose and 1% oregano essential oil	Showed an inhibitory effect against *Escherichia coli* and *Pseudomonas* spp. on the surface of beefsteaks[49].
	Edible Casein films with the addition of antimicrobial agents such as Carvacrol and essential oils.	It protects products that are prone to oxidation or moisture showing an inhibitory effect against microorganisms[8,10].
	Nanofibrils of Whey protein self-assembled with trehalose and glycerol into plasticized coatings.	These plasticized coatings protect freshly cut apple slices from browning and weight loss; which helps to retain their total phenolic content[17].
Nanocarriers	Fish gelatin film extracted from fish skin as nanoparticles	Acts as a nanocarrier for controlled delivery of various food supplements and additives[4].
Nanohydrogels	Hydrogels are produced from chemically modified wastes of fish protein (Whitemouth croaker) isolates.	These hydrogels can be used for dehydration processes in many industries such as food[40].
	Hydrogels of self-assembled casein-Cs, gum-starch and collagen-gellan hydrogels are used to load L-cysteine, N-acetyl-L-cysteine and anthocyanins respectively.	These hydrogels have applications in industries in the delivery of bioactive compounds leading to food products having better functional properties[5].

Table 2
Plant-based proteins nanostructures and their applications

Nanostructures	Examples With Compositions	Applications
Nanoencapsulation	Better encapsulation efficiency of Curcumin is achieved by loading with gliadin–lecithin nanoparticles.	These nanoparticles also enhance the antioxidant property of Curcumin[84].
	Encapsulation of bioactive compounds like Tangeretin by the nanoparticles of zein together with β-Lg	This encapsulation helps in the delivery of active compounds e.g. nisin, catechin etc[92].
	Nanoparticles of soya protein isolate are used to encapsulate vitamin B12 which increases its intestinal transport.	This kind of encapsulation improves the bioactive compound delivery[90].
	A new encapsulation technique called electrospinning is used to load Zein fibers with Gallic acid.	This new kind of encapsulation technique is used by the food packaging industry[72].
	Encapsulation of Curcumin achieved with the loading of β-Lg nanoparticles	Encapsulation Efficiency improved by >96% increasing its solubility also[63].
	Loading of resveratrol with zein-pectin core-shell nanoparticles encapsulation	This Encapsulation with great antioxidant potential has found its use in nutraceutical supplements and functional foods[24].
Nanoemulsions	Nanoemulsions of essential oils e.g. Cinnamon oil are used in the delivery of Vitamin D.	Essential oils when incorporated in nanoemulsions give a better alternative to synthetic additives because of their bioavailability[47].
	Emulsions of fish oil with wheat gliadin are examples of effective encapsulation.	This emulsion is very effective in inhibiting the lipid oxidation of fish oil[56].
Nanocoatings/ Nanofilms	Coatings and films based on quinoa protein and starch nanoparticles	These coating and film coatings are good barriers against the transport of water vapors. Carbon dioxide and oxygen[2].
	Protein-based self-assembled coatings of curcumin/oat β-glucan/lactoferrin and pea protein isolate/curcumin/ methoxyl pectin were developed with antioxidant properties.	These coatings are used to minimize lipid oxidation of foods[85,87].
Nanofibrils	Zein fibers encapsulate gallic acid using electrospinning.	Protein-based nanofibers are possible nano vehicles for the delivery of bioactive compounds[45].
Nanosensors/ Nanobiosensors	The development of Biomimetic sensors and smart biosensors using protein & biomimetic membranes is quite efficient.	Such nano biosensors are useful in the detection of mycotoxins and other pathogenic contaminants present in food[14].

Depending on ultimate application and properties other proteins like gluten, albumin, hemoglobin, fibrinogen and casein are used in various sectors of the food industry. Being hydrophilic in nature, casein found various applications in hydrophilic environments as its nanoparticles get dispersed instead of aggregation in an aqueous medium[58].

Applications of Protein-based nanostructures in food sectors: The three major components of food i.e. lipids, carbohydrates and proteins exist in the nano range. Protein is an essential nutritional component and is an excellent source of food-grade nanomaterials**.** There has been a raised interest in protein-based nanostructures in the last decade[54,66]. Proteins are large bio-molecules fabricated from one or more amino acid chains. These bio-molecules exhibit great nutritional value, stabilization, elasticity and protection. Proteins are usually water-insoluble in fibrous and globular forms. In formulated food items due to their rich nutritional value and ligand-binding properties, food proteins may serve as a bioactive molecule effectively[9].

The physicochemical properties of proteins depend on the quantity and sequencing of various amino acids in the polymer chain. Some of the functional properties such as water-binding capacity, gelation-emulsification and foaming ability are attributed to proteins[13]. The production of protein-based systems is based on the selection and combination of proteins based on their intrinsic and extrinsic factors.

Also, in a protein, the type and number sequence of amino acids determine molecular weight, conformation, hydrophobicity, electrical charge, physical interactions and other functional properties[9]. As a result of the adaptability of protein structure, many protein-based structures are formed depending upon the application. The protein-based structures developed so far are coatings and films, gels, hydrogels, fibers and particles[71]. Both animal and plant-based proteins have been extensively used for the designing and production of protein-based nanostructures. However, animal source proteins can be advantageous due to their large absorbability, degradation end-products and low toxicity[11].

Self-assembled proteins: Numerous reports are available on the development of functional foods, hydrogels, coatings/films and additives from the self-assembly of proteins obtained from different sources like animals, microorganisms and vegetables[36]. Also, the proteins from different origins can be co-assembled or the interactions between protein-polysaccharide may result in the formation of assembled multi-component structures[20].

Fig. 2 represents the various forms of self-assembled proteins. Milk proteins are the most investigated protein of animal origin for the self-assembled structure development[88]. Few researchers have also focused on the use of egg white proteins (EWP) to produce self-assembled proteins for micro and nanocarrier with its potential of rich nutritional value, easy digestibility and amphiphilic properties[12].

Micro and nanoparticles of whey protein isolate (WPI) microgels with their potential applications in pharmaceutics and foods have attracted a growing interest recently. WPI or pure α-lactalbumin and β-lactoglobulin micelles were used for encapsulation and delivery of hydrophobic active compounds[46].

Zein, the byproduct of the corn sugar industry is soluble in alkali and aqueous solutions of common polar organic solvents. The amino acid sequence of vegetable protein zein contains more than 50% hydrophobic moieties that make them an ideal candidate to self-assemble into spherical particles making them a suitable carrier for the effective delivery of food ingredients, nutraceuticals, oil, drugs and other bioactive molecules[79,89]. Owing to water-insoluble nature of zein, its emulsion gels can be prepared using different types of oils.

Zhang et al[91] showed that the hydrophobic interactions between the oil and solvent can be altered by changing the type of oil and solvent quality by which the properties of self-assembled zein emulsion gels can be managed. These emulsion gels found applications in the food industry such as the sustained and controlled release of various food additives. Gluten is extracted mainly from wheat while its small quantities can also be obtained from other cereals like rye, oats and barley[22].

Gluten is mainly used for the improvement of the properties of the bread flour and as an additive in baking products. Gliadins and glutenins are the two components of wheat gluten, out of these, only gliadins are soluble in alcohol. The desolvation technique using ethanol has been adopted for the fabrication of gliadin nanofibrils and nanocapsules and results show that pH plays an important role in these nanofabrications[30]. However, the self-assembled glutenin nanoparticles are less significant.

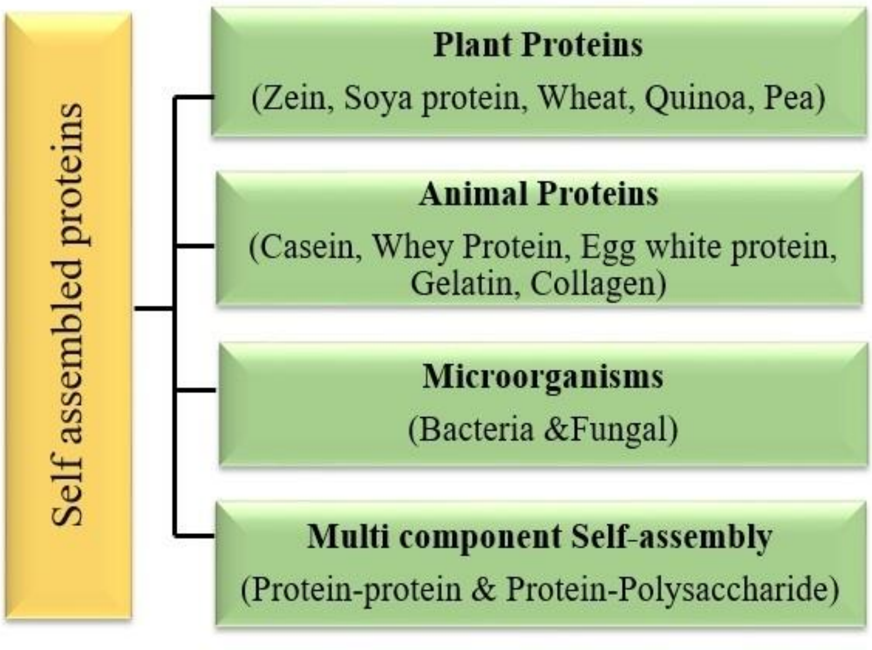

Figure 2: Various forms of Self-assembled Proteins

Due to the high nutritional value, antioxidant properties and high content of lysine, quinoa seed proteins have gained much attention for the fabrication of self-assembled nanoparticles[39,48]. Successful delivery of betalain (pigment) using self-assembled nanoparticles of quinoa has been reported by Martínez et al[39]. Presently, novel nanostructures including the self-assembly development containing soy proteins are focused to deliver the bioactive molecules having reduced bioavailability and low water solubility[59,69].

Different forms of self-assembled proteins from various sources can be utilized for extremely organized structural development with various morphologies in food applications in the form of particles, micelles, hydrogel and films. Few self-assembled proteins are discussed with their application in food technologies.

Gels and Hydrogels: Both gels and hydrogels are cross-linked polymers having three-dimensional structural organization. Gels being typically weak and soft can be made tough and hard by immersing in a definite fluid whereas hydrogels are amphiphilic or hydrophilic, they can easily swell and acquire a large capacity of water[59]. The increasing attention on protein-based nano hydrogels is due to their excellent ability to deliver the loaded compounds precisely at the exact location in the gastrointestinal tract. Nanohydrogel produces a response (physicochemical changes like swelling) to changing the nearby environment (temperature or pH).

The stability of chemically cross-linked gels is high due to covalent bonds present between various polymer chains, though the stability may vary under different conditions and cleavage of covalent bonds[6]. These cross-linked gels tend to swell on hydration till a state of equilibrium is achieved in response to stimuli[3]. Globular proteins of whey and soy proteins on heating cause molecular unfolding, exposing hydrophobic patches and thiol moieties, consequently, resulting in hydrophobic interactions, gelation and disulfide bonds[29].

Protein-based gels are used in food applications as they are safe for consumption. Gels exhibit excellent antimicrobial activity and also control the product humidity that is why they are used in food packaging[73]. Presently, gel-like nano-structures are effectively utilized for encapsulation and controlled release of highly valuable and unstable aromatic compounds or bioactive ingredients that have a positive effect on human health. Besides this, nano hydrogels also found applications in innovative food preparations[31].

Owing to their nutritional value, biodegradability, low cost and purposeful physicochemical and functional attributes, soy proteins have gained interest in the food area. Currently, soy protein is massively employed in protein-based infant formulations and efficient delivery of bioactive molecules and nutraceuticals. Being a plant-originated protein, soy protein serves as a safer delivery system due to the low possibility of transmitting zoonotic diseases when compared to animal-originated proteins[82]. Many studies have been reported using milk-derived proteins i.e. whey-protein-based products that include whey protein concentrate (WPC) or whey protein isolate (WPI) and its components especially bovine serum albumin and β-lactoglobulin protein-based hydrogels preparations for encapsulation and delivery of micronutrients and bioactive-molecules[1].

Edible hydrogels made of whey proteins are ideal for delivering minerals with the aim of improvement of nutrients[38]. Owing to the availability of functional groups and self-assembling availability, protein/peptide-based nanohydrogels are much superior compared to polysaccharide-based nanohydrogels. Moreover, hydrogels from fish proteins show reversibility of swelling capacity that can be used repeatedly without any loss of its hydration capacity[41].

Hydrocolloids: One of the important organoleptic property is aroma which greatly affects the quality of food. The aroma of the food greatly influences the food's value and its acceptability. Hydrocolloid interactions in food matrices are one of the emerging areas of research as hydrocolloids can influence the aroma. Aroma compounds show several positive impacts on human health. Hydrogels can play a significant role in reducing plastic consumption as they may be used in the manufacturing of new, bioactive and edible packaging materials. Hydrogels also meet the food technology and market requirements and are also used as lipids substitute in various food products[57]. Lipid substitutes like carrageenans, pectin and starch are generally used by food industries to retain the properties of removed lipids[43]. Due to increased awareness of the importance of a healthy diet, more attention has been paid to hydrocolloid research[68].

Emulsifiers: One of the promising applications of nano-emulsions is to inflate the bio-availability and accessibility of hydrophobic bioactive compounds[91]. Also, it has been used for the incorporation of active compounds into eatable coatings specifically fabricated to enhance the shelf life of foods. The use of emulsifiers to enhance the flavor and texture of food products along with the stability and shelf-life of foods has increased the consumption of processed food items including beverages[78]. Both plant and dairy-based protein and peptide emulsifiers have been widely applied in foods as they form a protective film in the formed emulsions. Whey proteins are being widely used in nano-emulsions as they possess amphiphilic properties and can be used as crucial emulsifiers in food applications[93].

Applications of protein-based particles are now getting big interest in the stabilization of Pickering High Internal Phase emulsions (HIPEs) with promising future in the food industry. Proteins in combination with polysaccharides and polyphenols are now being highly utilized in the formation of multilayer emulsions providing them a better surface activity and great functionality. Protein-based pickering particles result from the nanoparticle-based structures of both plant and animal proteins such as zein, kafirin, gliadin, gelatin and whey protein. Also, protein nanoparticles coated with multiple emulsions provide enhanced stability, good oxidative stability, high resistance to digestive enzymes and prolonged release of bioactive compounds[64].

Coatings and Films: Coatings and films are thin layers based on the thickness, they are used as a barrier against physical, microbiological and chemical contaminants. The thin coating on vegetables and fruits helps in reducing the transfer of moisture, water vapors, oxygen and carbon dioxide. Because of the adverse effects of non-biodegradable materials on human health, much attention has been made in developing biopolymer-based films, especially protein-based[19,76].

In general, self-assembled protein-based films are widely used in the food industry as they have low water vapor permeability, good optical properties, excellent fat barrier properties, acceptable mechanical properties and selective permeability to CO_2 and O_2. Few reports are available regarding the manufacturing of self-assembled protein-polysaccharide and protein-protein films. Gómez-Estaca et al[19] have shown the water-sensitive nature of protein-based films that subsequently result in the reduction of physicochemical properties and integrity. Hence, the water sensitivity can be efficiently reduced by the self-assembled protein-based films. Furthermore, these films also improve the mechanical properties of the materials.

Whey protein isolate (WPI) along with zein protein was used to fabricate a composite edible film that had combined physicochemical properties of each protein[74]. Composite films from soya protein-isolate (SPI) and cellulose at a 95,5 ratio were also obtained by self-assembly[26]. These self-assembled composite films show enhanced Young's modulus values and increased tensile strength with more rigid mechanical properties while a slight decrement in elongation at break value was observed in comparison to bare SPI films. The research carried out on the self-assembly of protein-polysaccharide composite films showed increased Young's modulus values. Moreover, it was observed that films manufactured from chitosan and shrimp waste by self-assembly in the presence of Ca^{2+} ions exhibit good antimicrobial and antioxidant properties[7].

Other applications: Biosensors made from the self-assembly of proteins have been effectually employed for the detection of microorganisms in food. Antibodies produced by *S. aureus* and *E. coli* were used as receptors in the self-assembled proteins-based biosensors for the detection of these pathogenic microorganisms. The developed sensor can efficiently detect the presence of *S. aureus* and *E. coli* up to 1.04×10^3 CFU/mL and 2.05×10^3 CFU/g in chicken rinse water while in pure water these pathogens can be detected in the 10^2–10^6 CFU/mL range. Thus these antibodies containing self-assembled microbial protein electrochemical sensors found great potential in the food industry as they can rapidly detect the presence of pathogenic bacteria[32].

Conclusion

Over the last few years, there has been expeditious growth in protein-based nanostructured materials. From an economic perspective, protein being a natural polymer is cheap, renewable and easy to process, making it a captivating material. Based on the processing methods, protein nanostructures can be tuned for more specific applications with their resulting properties. By self-assembly, proteins can be formed into films, hydrogels, micelles etc. with varied morphologies in food applications. As they are safe for consumption, protein-based gels are used in food packaging providing antimicrobial activity and humidity control. Also, these gels can be used for the controlled release of bioactive and aromatic compounds.

Protein-based nano-emulsions extend the shelf life of various food products due to their low water vapor permeability, good optical properties, excellent barrier properties and selective permeability to CO_2 and O_2. The development of electrochemical-immuno-sensors has shown good potential for the fast detection of pathogens in the food industries. In the food industry, biosensors are a steadily growing trend as rugged detection techniques for food quality and safety that are time-saving and cost-effective also. Composite films with a combination of proteins and other higher molecular weight moiety for the desirable formulated products will be a challenge in exploring and extending their applications to new fields.

To meet the requirements in accordance with the standard food safety regulations extensive study is required. Moreover, with uncovering of a new nanoscale moiety of proteins, there is a need for much more exploitation and the emergence of new field applications. Based on the structural conformation, molecular interaction and functional properties of various proteins, different studies are focused on the effect of novel technologies providing a fundamental understanding of the mechanism in various food processing conditions.

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