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Application of Silk Fibroin Nanoparticles based Edible Coating Material for Postharvest Shelf - Life Extension and Preservation of Food Products

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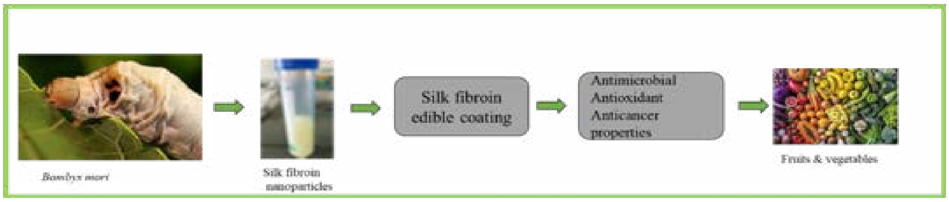
Abstract

Nanotechnology is a burgeoning discipline that adapts to fresh and improved use in food systems relative to previous technologies, despite its broad application in agriculture, biochemistry, medicine, and several industries. By implementing innovative technologies, it is possible to efficiently incorporate them into many parts of food production, development, manufacturing, packaging, storage, and distribution. Nanoparticles occupies the most fundamentally advanced technology in nano-based food science. Using a broad range of nanostructured materials and nanomethods, such as liposomes, polymeric nanoparticles, nanoencapsulation, nanotubes, nanocomposites, packaging, and nanosensors. Silk Fibroin (SF), a biomacromolecule based on proteins, is very biocompatible, biodegradable, and has a low immunogenicity. Due to these characteristics, silk fibroin nanoparticles, or SFNPs, are beneficial across several sectors, including medical and food. The creation of SF-based nanoparticles as edible coating materials extends food shelf life and protects food components while also fortifying and supplementing nutrients. The phytochemical activities of SFNPs, including their antibacterial and antioxidant properties, are summarized in this review. The possible uses of *silk fibroin nanoparticles in food, such as food additives and food packaging, which may be able to meet customers increasing demands about the food's safety and nutritional value. The techniques of food preservation used to preserve or safeguard food quality are the major topic of this review article. Natural food preservatives are also discussed as a safer alternative to chemical preservatives for human consumption.*

Keywords: Natural Preservatives, Nutritional Values, Preservation, Shelf Life, Silk Fibroin Nanoparticles

Graphical Abstract



Introduction

Nanotechnology has introduced novel food processing techniques with the aim of enhancing the physicochemical qualities of food and enhancing its nutritional stability and bioavailability (Patra, 2018). Nanoparticles are used in a wide range of industries because of their exceptional mesoscopic qualities, which include increased surface area, high reactivity, small particle size, high strength, quantum effects, and ductility (Ariyarathna, 2017; Omerovic, 2021). Lopez-Rubio (2019) stated that the modernization of the food and pharmaceutical industries is comparable to that of the medicine delivery. Because of the special characteristics that distinguish them from bulk materials, such as physicochemical and biological properties, research on the synthesis, classification, applications, and evaluations of nanomaterials has made it possible for scientific innovation to improve and transform the entire agri-food industry in the ensuing decades (Bouwmeester, 2018; Siddiqi, 2018).A plethora of novel products with enhanced sensory attributes, texture, taste, stability, and other food quality elements have been made possible by the application of nanotechnology in food systems (Anandharamakrishnan and Parthasarathi, 2019). Researchers and business associations have already noted that practically every aspect of the food industry, including agriculture, food processing, safety, packaging, and nutrient delivery, can benefit from the application of nanotechnology (Pathakoti 2017; Sahoo, 2021). Many studies have examined the feasibility of using nanoparticles in food quality control, innovative packaging, food safety implementation, and the development of food products with modified functions and nutrition (Ariyarathna, 2017; Noruzi, 2016; Pathakoti, 2017; Singh, 2017; Wyser, 2016).Identifying food-related diseases, developing suitable diet plans for a range of target audiences, such as the elderly, geriatric patients, and specific situations, and employing nanoencapsulation to guarantee the sustainability of food production are further applications of nanotechnology. Furthermore, food fortification using nutrition nanotherapy can provide one-of-a-kind products by developing intelligent, smart systems for controlled nutritional delivery (Sahoo, 2021).

Preservatives, flavourings, encapsulated food ingredients, antimicrobial sensors, packaging compounds, and other nanoparticles and nanoscale food additives can be used to identify food pathogens, providing information about a food's quality standards (Bott, 2014). Nanotechnology is frequently used as an antibacterial agent in food preservation, food additives, and food packaging (particularly with Cu/CuO, Ag, MgO, TiO2, ZnO, carbon dots, mesoporous particles, and graphene, among other substances) (Omerovic, 2021; Pathakoti, 2017). Nanotechnology provides several advantages over traditional packaging approaches, including improved mechanical barrier, heat resistance, and biodegradability (De Azeredo, 2009). Because of their superior antibacterial properties, nanomaterials can be employed in conjunction with nanosensors to detect food degradation (McClements and Xiao, 2012). Antimicrobial packaging (structured polymeric films) or encapsulating materials inhibit bacterial growth on the packaged food's surface by spreading active substances onto the food or into the surroundings (Drago, 2020). Active packaging employs antimicrobial nanoparticles to protect food from hazardous and spoilage-causing microbes, extending shelf life and retaining freshness. They are also added in active packaging to make it more resilient, lighter, and less susceptible to O_2 (Hoseinnejad, 2018; Omerovic, 2021; Sharma, 2020).

Nanotechnology is being used in the food sector to improve food security by detecting illnesses or contamination in food throughout manufacturing, processing, packing, storage, and transportation (Nile and Kai, 2021; Wang, 2021). Nonetheless, using modified nanoparticles in food products increases individuals' exposure to oral nanoparticles (Cao, 2016). People are exposed to nanoparticles primarily through the oral consumption of nanoparticle-enhanced food and the ingestion of nanoparticles that have migrated from packaging (Wang, 2021). Ingestion of nanoparticles has been linked to DNA damage (Lu, 2015), protein denaturation (Hong, 2017), and the activation of oxidative stress responses (Khanna, 2015). Several studies have linked gastrointestinal and secondary organ damage to oral nanomaterial intake, particularly solid nanoparticles (Cao, 2016). This underscores the importance of closely monitoring the usage of nanoparticles in food products. As a result, before adequate monitoring of nanoparticles in food can be implemented, it is critical to quantify the level of exposure and create efficient approaches to assess nanoparticle toxicity and food safety (Sahoo, 2021).

Food preservation and packaging are now possible without causing harm to the environment or human health owing to rapid advances in nanotechnology in the food and agricultural industries (Singh, 2017). There are edible biopolymers (Pradhan, 2015) and semi-synthetic polymers (Pavoni, Perinelli, Bonacucina, Cespi, & Palmieri, 2020) available for food packaging. Chitosan, starch, alginate, pectin, xanthan, gellan, psyllium, carrageenan, basil seed, arabic gums, corn, cellulose and its derivatives, such as CMC (carboxymethylcellulose) and MC (methylcellulose), pullulan, alginate, and guar gum (Salehi, Perishable fruits and vegetables are thinly coated with edible nanoparticles using a variety of methods, including electrospun nanofiber coating, spray coating, and dip coating (Ghorani and Tucker, 2015).

Perishable fruits and vegetables have been coated with a variety of edible thin-film coatings, including dip-coating processes using diverse biopolymer composites. Banana fruit coated with carrageenan composite (a carboxymethyl cellulose blend) had a six-day shelf-life increase compared to the control (Dwivany, Aprilyandi, Suendo, & Sukriandi, 2020). Rice starch edible covering combined with sucrose esters delayed banana ripening by 12 days when stored at 20 ± 2 ◦C. (iii) Senna, Al-Shamrani, and Al-Arifi (2014) found that edible coatings consisting of gamma-irradiated plasticized poly(vinyl alcohol), carboxymethyl cellulose, and tannin extended the shelf life of banana fruit from nine to nineteen days. (iv) The efficacy of different edible coverings for apple fruit, such as glycerol, soyabean gum, jojoba wax, and arabic gum, was studied during cold storage. Silk fibrin (SF) is a biomacromolecule composed of proteins. It is commonly used as a biomaterial in the food industry in the form of films, hydrogels, spheres, electro spun fibres, and three-dimensional scaffolds.The ability of SF-based nanoparticles to increase cell adhesion and proliferation, as well as their biodegradability, enhanced biocompatibility, chemical manipulation capabilities, and cross-linking potential, make them an appealing choice for extending the shelf life of foods.

The aim of this review is to produce coating materials that are safer, edible, and biodegradable in order to improve food product preservation after harvest. We also examined and highlighted relevant research on silk fibroin nanoparticles, which are used in a variety of food industries, with a focus on the development and application of nanocomposite-based active or smart food packaging, with a particular emphasis on biodegradable polymers and antibacterial nanofillers.

Silk

Silk Structure and Extraction

Silks are protein biopolymers that are produced by arthropods such as silkworms, flies, spiders, and silverfish. According to Xiong et al. (2018), differences in the composition of amino acids enable different arthropods to produce silk components with unique structural characteristics. There are differences in the mechanical properties of different spider and silkworm silks. Moreover, different types of silk produced by the same species are caused by other factors that affect the quality of silk, such as the environment and the diet of arthropods (Cristina BeldaMarín et al., 2020). Mulberry worm silks are currently the most widely used silks for textile and medical applications. Even though certain spider silks have more extensibility, toughness, and durability than others, it is difficult to generate high-yield spider silks industrially due to the cannibalistic nature of spiders. Still, domesticated *Bombyxmori* silkworms were used for industrial silk production decades ago. The next sections only address B. mori silk because silkworm silk is almost exclusively used for medical and related applications.

Silkworm *(Bombyxmori)* Silk Fibroin

Silk fibroin (SF), a protein-based biomacromolecule, is made up of huge, repetitive, modular hydrophobic domains separated by microscopic hydrophilic groups. According to Kaplan (D.L., 1998), the main structural components of *(Bombyxmori)* SF are glycine (Gly) (43%), alanine (Ala) (30%), and serine (Ser) (12%). SF is a heterodimeric protein with a single disulphide link between the heavy (H) chain (~325 kDa) and the light (L) chain (~25 kDa), located at cys-172 of the L-chain and cys c-20 (the twentieth residue from the C terminus) of the H chain. P25, a 25 kDa silk glycoprotein, was also found to interact noncovalently with disulfide-linked heavy and light chains. Furthermore, the chains of SF comprise bulky and polar side-chain amino acids, specifically acidic, valine, and tyrosine amino acids (Mondal, M., 2007).

SF's H-chain alternates between hydrophobic and hydrophilic blocks, just like in amphiphilic block co-polymers. It gives the silk thread crystalline properties and is hydrophobic (Sehnal, F., 2004). Gly-X repetitions, where X is any of the amino acids Alanine, Serine, Threonine, or Val, can form anti-parallel β-sheets, giving the fibre stability and mechanical properties. These repeats are situated in the hydrophobic regions of H chains. In comparison to the length of the hydrophobic repetitions, the hydrophilic connections that link these hydrophobic domains are non-repetitive and very brief (Bini, E, 2004). It is the amorphous component of the secondary structure, consisting of bulky, polar side chains. Silk is flexible due to the random coil chain conformation present in amorphous blocks (Vepari, 2007). The L-chain tends to be hydrophilic and flexible. The P25 protein may be critical for maintaining the complex's stability. H-chain:L-chain:P25 molar ratios are 6:6:1 (Hardy, J.G., 2008).

Chemical Structure and Properties of Silk Fibroin

Silk fibroin (SF) is a natural polymer that is spun by numerous species, including silkworms and spiders. The silkworm *Bombyxmori* and the spider Nephilaclavipes create dragline silk, which is the most well-studied form of silk. The United States Food and Drug Administration (FDA) has approved SF, a natural protein polymer, as a biomaterial. Spiders' more aggressive behaviour, as well as the more sophisticated and smaller volumes of silk combinations formed in orb webs, have hampered commercial manufacturing of spider silks, as opposed to the established supply chain available for silkworm silk (Kundu, J, 2010).

Silk Fibroin Biocompatibility

An essential stage in the development of a medical device is determining its biocompatibility. Biocompatibility refers to the ability of a biomaterial with minimal cytotoxicity and immunogenicity to be “accepted” by the organism in order to avoid rejection. However, biocompatibility is affected by the material’s structure as well as how it is used and interacted with over time. As a result, each material must be tested in its final state to ensure compatibility. Silk materials have been utilised to manufacture silk sutures for a long time, however hypersensitivity has been reported on rare occasions. Because silk is an alien material, implants often cause a moderate inflammatory response. According to Cristina BeldaMarín et al. (2020), this immunogenic reaction may be caused by residual sericin or the use of non-degummed silk in the material. Materials containing fibroin or sericin, a single silk protein, have not been found to produce immunogenicity (Cristina BeldaMarín et al., 2020). Numerous studies have demonstrated the biocompatibility of alkali heat-degummed silk products, such as SF electrospun mats, films, gels, and microparticles. In vivo studies revealed that silk, compared to type I collagen and PLA, reduced inflammation. The FDA has approved the use of silk for medical purposes in the United States(Cristina BeldaMarín et al., 2020).

Preparation Methods of Silk Fibroin-Based Nanoparticles

There are several approaches for producing SF-based nanoparticles, including electrospraying, mechanical comminution, salting out, desolvation, and supercritical fluid technology. The synthesis of SF-based nanoparticles for medicinal and food applications necessitates careful analysis of the advantages and disadvantages of each method. More research is needed in the challenging subject of SF nanoparticle manufacture. Because SF is a protein with a high molecular weight, regulating the production of nanoparticles is difficult. Furthermore, when subjected to high shear, heat, salt, and pH changes, SF tends to self-assemble into gels or fibres.

Ideal Properties of Preservatives

1. It must not to cause irritation.
2. To keep the uniformity of the product.
3. To keep things healthy and palatable.
4. It neednot to be poisonous.
5. It need to be chemically and physically stable.
6. It need to work well with every other component.
7. It expected to function well as an antibacterial agent.
8. Its activity should be strong.
9. Its shelf life needs to be longer (Hamid, 2012).

Maintaining food quality is necessary to make sure that foods with good nutritional contents are used, which is crucial for our overall health. Therefore, the best approach to maintain food quality and stop it from deteriorating is to use preservation techniques. These days, there are many different kinds of preservation techniques that may be employed, either using traditional or cutting-edge preservation technology, to keep food items’ quality intact for an extended amount of time. Additional food preservatives, which fall under the categories of artificial and natural preservatives, are used in some of these preservation techniques. While many artificial food and cosmetic additives are thought to be harmless, it is best to minimize their usage because some of them have been shown to be very toxic and carcinogenic. Preservatives and additives made of synthetic chemicals should generally be avoided as many of them have not undergone adequate testing (Sabir, 2016).

Function of Preservatives

1. To improve or preserve food's nutritional value.
2. To improve quality and cut down on waste.
3. To increase acceptance among consumers
4. They prevent microorganisms from growing.
5. They provide processed foods a comparatively longer shelf life.
6. Salt and potassium nitrate, two popular preservatives, have been used for ages in
7. Wine and processed foods (Mirza, 2017).

Food Preservation Methods

1. Drying: Reducing water activity to a level that stops or slows bacterial development makes drying one of the oldest ways for preserving food. Drying also makes things lighter.
2. Pickling: Anaerobic fermentation is the method used to preserve food by pickling. The dish that is produced is known as a pickle. The meal tastes sour or salty as a result of this process. Vegetable oil, vinegar, alcohol, and brine are common pickling agents. A pH of less than 4.6 is another distinctive feature that is adequate to eradicate the majority of germs. Perishable foods can be kept for months by pickling them (Sharif, 2017).
3. Canning: When done correctly, canning is a vital and safe way to preserve food. Food is cooked, sealed in sterilized cans or jars, and then the containers are boiled to destroy or weaken any residual germs as part of the canning process.
4. Freezing: These days, the most popular techniques for preserving food are probably freezing and refrigeration. The goal of refrigeration is to slow down bacterial activity to the point where food spoils much more slowly. (Leistner, 2000; Wiley, 1994).
5. Jellying: Cooking food in a substance that solidifies to produce a gel can preserve it. These substances include arrowroot flour, gelatine, agar, and maize flour.
6. Vacuum packing: Typically, food is vacuum-packed in an airtight bag or bottle. Bacteria that require oxygen to survive are deprived of it in the vacuum atmosphere, which slows down spoiling. Food can be harmed by air, which can lead to rusting, the spread of bacteria, or missing goods. Foods that travel great distances can be preserved using this strategy for weeks or months if they are chilled (Leistner, 1992).
7. Water bath: Using this method, food is kept firmly wrapped inside a glass container filled with water. After that, the bottle is put in a saucepan with water in it that reaches the jar's top. Boil for half an hour, then stop. Before there is a rapid temperature change that could cause the bottle to break, leave the flask inside the container until the water has completely cooled. The food may be preserved using this method for several months or perhaps more than a year (Lado and Yousef, 2002).
8. Dip coating: The food is soaked in a container of coating solution using dipping method, Foods with complex or rough surfaces that require complete coating (antibacterial, antioxidant, nutritional, etc.) benefit greatly from this technique. Following dipping, the food item is dried at ambient temperature (air drying) or with the use of a specialized drier to remove the residual coating. Broccoli (H. Fang, 2022), star fruit (D. Boyaci, 2019), fish, persimmons, and walnuts (M.N. Shaukat, 2023) are among the many plants from which dyes have been created.

Application Edible Coating for Fruit/ Vegetable

Due to their biological activity, fruits and vegetables lose some of their solutes after being harvested. Fresh fruit and vegetable postharvest losses result in reduced weight loss, color changes, structural alterations, and browning. Fruits and vegetables with characteristics that are readily harmed by cold storage that must be delayed in order to prevent ripening changes include softening, ethylene generation, changes in pigment, respiration rate, reduced weight loss, and antifungal activity (L. Saidi, 2021). However, fruits and vegetables degrade at temperatures below 12◦C, and cold storage is insufficient to keep their freshness at peak levels throughout marketing. Use edible coatings to lengthen postharvest life and save production costs as a result, as they require an efficient renewal.

Application Edible Coating for Red Meat and White Meat

Red meat and white meat are the two categories of meat found in trade commodities from WCRF/AIR. Amino acids, minerals, and protein are abundant in meat. Several modified atmospheric preservation techniques, such as hydrostatic pressure, coating irradiation, and biomarco molecular coating, are used to preserve meat quality. There are two types of meat that are considered the best: white meat, which includes fowl, chicken, duck, turkey, and rabbit, and red meat, which includes cattle, hog, lamb, and goat. Texture, color, flavor, nutritional value, and a robust UV protection are all qualities of high-quality beef products (A.A.F. Fallah, 2022). Edible coatings are an additional option as consumers are aware of the dangers associated with employing synthetic substances.

Biological Activities of Silk Fibroin

Antimicrobial Property of Silk Fibroin

A recent study indicated that B. mori silk fibroin had low to moderate bactericidal activity (W. I. Abdel-Fattah, 2015). The protein’s high glycine content helped explain this. However, Kaur et al. discovered that the natural antibacterial activity of B. mori silk fibroin was insufficient or absent (J. Kaur, 2014). The bactericidal effect that was seen might have been influenced by the many small peptides that were left behind from silk cocoons. Among the most common peptides were seroins and protease inhibitors, which have anti-bacterial, anti-viral, and anti-fungal properties (J. Pandiarajan, 2011; C. P. Singh, 2014). They can also protect pupae against invasive infections (X. Guo, 2016). On the other hand, several studies have shown that silk fibroin actually encouraged the growth of bacteria. It has been shown that the silk fibroin’s nanopatterned surface characteristics encourage the development of bacteria (F. Xue, 2015). Furthermore, the silk fibroin/glycerol composite film promoted the growth of biofilms (Y. Tabei, 2011). Films, hydrogels, woven matrices, and non-woven matrices are often made from silk fibroin and are utilized as raw materials for wound dressings. The majority of these tiny peptides were eliminated or inactivated during the degumming, dissolving, and purification procedures, which is why purified and processed silk fibroin typically lacks fungicidal or bactericidal qualities. Silk fibroin’s antimicrobial (i.e., antibacterial or antifungal) qualities can be enhanced for use as a wound dressing by surface modification or the addition of antibiotics, biocides, or natural extracts.

Antioxidant and Antitumor Activities

The antioxidant effects of sericin have long been known. It has been demonstrated to have a suppressive impact on lipid peroxidation in the gut due to its antioxidant ability; thus, it may be used to prevent colon cancer from growing and spreading (Kaplan, D.L, 1998). Using a mouse model of alcohol-induced liver injury, You-Gui et al. demonstrated that sericin can restore reduced antioxidant enzymes such as GSH, GSH-PX, CAT, and SOD to normal levels. Furthermore, sericin not only scavenges hydroxyl, superoxide, and DPPH radicals, but it also inhibits linoleic acid peroxidation (L. Saidi, 2021). In a subsequent in vitro investigation, numerous silk sericin hydrolysates shown a considerable reduction in power and ferrous ion chelating activity when compared to the control (I. Tontul, 2020). Similarly, when hydrogen peroxide is used, sericin has been shown to have antioxidant properties in the catalase and thiobarbituric acid reactive substances (TBARS)-induced oxidative stress in the feline fibroblast cell line. According to A. Gholamhosseinpour (2023), sericin-treated cells showed significant cell survival and restored cell membrane integrity, indicating that sericin has the potential to be used in cancer therapy. When mice were fed 1,2-dimethylhydrazine at a rate of 30 g/kg for 115 days, sericin had a good effect on health in terms of lowering colon adenocarcinoma, cell proliferation, and nitric oxide production (M. Torun, 2022). An in vitro experiment was conducted to explore the effects of sericin on the human colon cancer SW 480 cell line at two molecular weight ranges. Little sericin had a greater effect on cell viability by increasing cell cycle arrest in the S phase, causing cell death via caspase-3 activation, and down-regulating Bcl-2 expression. In the rat model of colon carcinogenesis, adding 3% sericin to the diet significantly reduced the colon's oxidative stressand tumor incidence (A.A.F. Fallah, 2022).

Functional Application in Food Industry

The food industry has received various recommendations for silk-based food packaging, demonstrating the material's versatility. Vegetables and fruits have been utilised to preserve silk-based materials such as dragline silk and SF. These coverings reduce transpiration, respiration, and microbial infections while conserving the plants' physiological and phytochemical qualities (P. J. Babu, A, 2021). A protein solution based on water that self-assembles when dipped in food was created utilising SF. Controlling dispersed gases through the thin SF barrier is a key part of keeping food fresh, which can be accomplished with water-based post-processing management. The thin, micrometre-ranged SF that coated the fruit helped to sustain post-harvest physiology by slowing cell respiration and water evaporation (B. Marelli, M.A, 2016). To create a coating solution, SF was hybridised 1:1 with poly vinyl alcohol (PVOH). Hybridisation improves the mechanical characteristics and gas barrier of SF by increasing its β -sheet content. The solution's effectiveness as a food preservative was tested on a recently sliced apple. Throughout the drying process, a bilayer structure was seen, with PVOH creating a second layer on top of the silk and the food and SF making direct contact. The coated fresh apples showed much less colour change and weight loss than the uncoated controls, which were stored at 4°C for more than 14 days (E. Ruggeri, 2020). Another study proposes that an edible coating might be created to improve the shelf life of apricots while preventing fungi from infecting them. Sterilized silk that had been degummed was prepared for a coating solution. To increase the quantity of the β -sheet, fresh apricots were coated with the solution and water annealed at different intervals. The coated but unannealed apricots had significant water loss but no fungal infection, whereas the water-annealed and coated apricots had a 14-day shelf life. After three days, the uncoated apricots began to deteriorate; after four days, the texture changed; and after seven days, full fungal development occurred (H.M. Tahir & N, 2019).

According to reports, the auspicious use of silk waste in the generation of thin films holds great promise for food coating. Researchers investigated utilising SF thin films, which are made from residual silk waste, as edible strawberry coatings. Two sets of thin films were produced, one utilising a water annealing process and the other without treatment. Strawberries with water-annealed thin-film coatings performed well in terms of weight loss prevention without compromising aesthetic appeal.An investigation conducted to check for metal contamination revealed that the silk fibroin that was removed from the garbage showed no signs of metal toxicity (N. Jaramillo-Quiceno, 2020). In recent years, an extensive variety of intelligent and active food packaging has been designed and manufactured. The use of nanoparticles in the development of nanotechnology for food packaging has shown tremendous promise in improving the qualities of currently available materials for food preservation and maintenance (P.J. Babu, 2022). Zhao and colleagues recently developed a silk-based thermoregulating hydrogel to use as an active food product packaging material. This hydrogel composite was produced by combining SF, cellulose, and n-octadecane. The latter functioned as a temperature buffer. It considerably delayed the rate of food decomposition by absorbing moisture from temperature-sensitive fruits (L. Zhao, 2018). Tao et al. developed an antibacterial packaging material using silver nanoparticles (AgNPs) and a hybrid of SF and polyvinyl alcohol. The matrix formed when SF and PVOH were mixed exhibited remarkable mechanical characteristics. The study of antimicrobial activity using these microorganisms indicated good suppression against both gram-positive and gram-negative food-borne pathogens, providing further alternatives for usage in the field of active packaging (G. Tao, 2017). In another investigation, SF films infused with active substances such as poly (ethylene oxide) (PEO) and thyme essential oil (TO) shown increased antibacterial activity. SF-PEO and TO cold plasma treated nanofibres may give seven days of protection against Salmonella typhimurium infection in poultry products (L. Lin, 2019).

Valentini et al. developed a hybrid composite for smart food packaging that monitors temperature-sensitive commodities using yeast and a single-cell fungus. This hybrid composite was laminated with parafilm, which has a high thermal expansion coefficient and can transition between two states: wrinkled and wrinkle-free. After applying the food surface at a high temperature and cooling to room temperature, wrinkling occurred due to the compressive strength of the SF/parafilm/yeast composite interface. Heating can reverse the process, allowing cloth to restore its wrinkle-free appearance. L. Valentini (2018) revealed that by activating the metabolism of bacteria found in regenerated silk, the shelf life was increased to more than seven days, despite the films' limited water permeability.

Conclusion and Future Perspective

Silk fibroin protein (SF), which is naturally occurring, odourless, and edible, possesses nearly all of the properties required to be a viable carrier for a wide range of high-tech applications. It is now being studied for a variety of biological and biotechnological uses. Many studies have investigated the impacts and applications of silk proteins as natural biomaterials in a range of settings. Silk fibroin nanostructures are harmless, biocompatible, and biodegradable. Because of their demonstrated antioxidant action in model food systems, silk fibroin nanoparticles are a promising possibility for developing a natural and safe food additive.

The capacity of silk fibroin nanoparticles to exhibit bactericidal activity against common food-related Gram-negative and Gram-positive bacteria highlights these particles' potential as a natural food preservative. It is critical to standardise the antibacterial spectrum and effective concentration when using silk fibroin nanoparticle solution as a natural preservative in food systems or packaging. Thus, future research should focus on (i) understanding how the silk fibroin nanoparticle solution influences the microstructure of food and food packaging, and (ii) utilising silk fibroin nanoparticles as helpful components and natural preservatives in food systems or food packaging. (ii) researching the metabolomics of silk fibroin nanoparticles in the gut microbiota; and (iii) creating a novel and sustainable delivery system for silk fibroin nanoparticles that enhances their stability and regulated release in food regions where microbial contamination may have occurred during post-processing. Additionally, it is critical to assess the silk fibroin nanoparticles' acceptable sensory ratings and potential synergistic effects with food systems or packaging components. In conclusion, adding silk fibroin nanoparticles as a functional element to food systems and active food packaging can be a calculated move to extend food product shelf life and lower food sepsis. We believe that the future of SF-based nanostructures is bright and exciting, particularly with the progress of technologies such as surface engineering and genetic engineering.

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