



Review

Revolutionizing seafood packaging: Advancements in biopolymer smart nano-packaging for extended shelf-life and quality assurance

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ABSTRACT

Food packaging is one of the most important strategies to prevent food damage or spoilage during storage and the supply chain. Among various food types, seafood, a high-value product, is particularly vulnerable to post-harvest quality loss and microbial contamination during storage. Although current plastic-based packaging materials are durable, they pose a serious threat to the environment. Therefore, research on natural biopolymers for packaging is a top priority for scientists, industries, and government bodies. Additionally, nanoengineering concepts enhance the physicochemical and functional properties of biopolymers, thereby revolutionizing the packaging industry. This review provides a comprehensive discussion on smart nano-packaging for seafood products. It focuses on advancements in biopolymer smart nano-packaging as a transformative solution for extending the shelf life and ensuring the quality of seafood products. Existing knowledge highlights the functionality of biopolymers and nanotechnology, but gaps remain in addressing practical applications, such as scalability, cost-efficiency, and consumer safety. This review bridges these gaps by providing a detailed analysis of biopolymer-based active and intelligent packaging systems, which integrate antioxidant, antimicrobial, and freshness-indicating properties. It emphasizes the unique contributions of nanoengineering to enhance biopolymer properties, offering innovative solutions to the seafood packaging industry while promoting environmental sustainability.

1. Introduction

The compound annual growth rate of the global seafood market is expected to be 7.2 %, increasing market value from USD 39.7 billion in 2022 to USD 56.2 billion by 2027 (Aquaculture products market, 2023). Seafood is a great source of proteins, omega-3 fatty acids, magnesium, calcium, iron, phosphate, zinc, iodine, and vitamin A (Maire et al., 2021). This biochemical content makes seafood highly perishable post-harvest due to indigenous enzyme degradation, oxidative changes, and microbial contamination (Koirala et al., 2023). Furthermore, during refrigeration, Gram-negative psychotropic bacteria (e.g., *Aeromonas* spp., *Pseudomonas* spp., and *Enterobacteriaceae* spp.) can proliferate and

spoil fresh seafood (Gokoglu, 2020). Changes in the physicochemical and microbiological characteristics of seafood significantly affect product quality and shelf life. Therefore, current strategies to prevent post-harvest quality loss include onboard chilling, synthetic additives (e.g., sodium metabisulfite), blast freezing, and packaging (Nirmal, Santi-varangkna, Rajput, Benjakul, & Maqsood, 2022). Among various strategies for shelf-life extension, packaging plays a crucial role in maintaining seafood quality (Sharmila, Muthukumaran, Kumar, Sivakumar, & Thirumarimurugan, 2020). The current packaging industry predominantly uses synthetic plastics due to their good barrier properties, durability, resistance to light and moisture, and cost-effectiveness (John, 2020). However, plastic packaging waste is a growing concern

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worldwide because of its non-biodegradable nature, environmental impact, and contribution to global warming (Vibha et al., 2022). This critical global issue has led to increased demand for biodegradable packaging materials to support environmental sustainability (Pirsa et al., 2023).

Biopolymers, including proteins, polysaccharides, lipids, polylactic acid, pullulan, xanthan, and polyhydroxyalkanoate gum obtained from natural sources, are promising alternatives due to their ability to form polymer films (Abelti et al., 2022; Abdolsattari et al., 2022). The widely investigated polysaccharides include cellulose, starch, alginate, chitosan, pectin, and κ -carrageenan (Xue, Zhu, Sun, Yang, Wu, & Li, 2023; Shankar et al., 2019). Proteins, another significant category, contribute to the development of strong and flexible biopolymer films. Common protein sources include gelatin, casein, soy protein isolate, whey protein, wheat gluten, and maize zein, each offering distinct mechanical and barrier properties (Baranwal, Barse, Fais, Delogu, & Kumar, 2022). Compared to synthetic plastics, biopolymers disintegrate, degrade, restore nutrients to the soil, and reduce the amount of waste (Wang, Euring, Ostendorf, & Zhang, 2022). Nanotechnology is currently being extensively explored to enhance the physicochemical, mechanical, and functional properties of metals and biomolecules. Incorporating nano-engineered particles into packaging materials has demonstrated improved barrier properties, thermal stability, and durability (Sun, Wang, Dong, Zhang, Li, & Wang, 2022; Tyagi, Salem, Hubbe, & Pal, 2021). Furthermore, nanotechnology enables the development of active packaging with ultraviolet (UV) absorption capacity, antioxidative and antibacterial properties, and intelligent packaging that can monitor and control food conditions (Primožič, Knez, & Leitgeb, 2021; Mahmud et al., 2022).

In a previous report, various strategies for formulating nanospheres, nanofibers, and nanoparticles for edible films and coatings were detailed (Koirala et al., 2023). That article specifically focused on edible coatings for seafood that can be consumed along with the seafood itself. The present review, however, explores biopolymer-based smart nano-packaging sheets for seafood products, designed for packaging and environmental sustainability purposes (not for consumption). Kontominas et al. (2021) reviewed advancements in seafood packaging technologies, including modified atmosphere packaging, vacuum packaging, active packaging, intelligent packaging, and retort pouch processing. Another research group examined sensor-based smart packaging for seafood products (Abedi-Firoozjah et al., 2023). Although these articles discuss smart packaging, they focus on specific applications—whether active, intelligent, or sensor-based—without emphasizing biopolymer materials. None of these articles specifically address nanoengineered biopolymer smart packaging. This review identifies this gap in the literature. In this context, seafood composition, post-harvest quality loss, and various natural polymers used in biopolymer packaging are examined. A comprehensive discussion is provided on active nano-packaging materials (with antioxidant, antimicrobial, and moisture regulation properties) and intelligent nano-packaging (with freshness, time-temperature, and leakage indicators) for extending seafood shelf life and ensuring quality assurance. Finally, concluding remarks and future directions for biopolymer smart nano-packaging are presented.

2. Seafood composition and spoilage

Seafood encompasses a wide variety of aquatic organisms consumed as food. The types of seafood can be broadly categorized into fish and shellfish, each offering distinct characteristics and nutritional profiles (Aakre et al., 2020). Fish can be further classified into lean fish, such as cod, haddock, and tilapia, which provide a lean source of protein, and oily fish, including salmon, mackerel, and sardines, which are rich in omega-3 fatty acids (Taşbozan & Gökçe, 2017). Shellfish, on the other hand, comprise crustaceans and mollusks, such as lobsters, crabs, shrimp, clams, mussels, oysters, and scallops, all of which are excellent

sources of nutrients. Shellfish are valued for their high protein content and minerals, such as selenium and copper (Faber et al., 2017). Seafood composition is characterized by a diverse array of macro- and micro-nutrients that contribute to its nutritional value. Docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA) are two omega-3 fatty acids found abundantly in seafood (Calder, 2018). Seafood is also rich in essential vitamins, including vitamin D and B vitamins, particularly vitamin B12 (Nordhagen et al., 2020). Aakre et al. (2020) reported that sardines are an excellent source of polyunsaturated fatty acids (PUFA: 3.1 %) and monounsaturated fatty acids (MUFA: 1.2 %) compared to anchovies (PUFA: 1.9 %; MUFA: 0.60 %) and Atlantic horse mackerel (PUFA: 0.31 %; MUFA: 0.12 %). Regarding vitamins, Atlantic horse mackerel has the highest level of vitamin D3 (28 $\mu\text{g}/100\text{ g}$), while anchovies contain the highest concentrations of vitamin A1 (125 $\mu\text{g}/100\text{ g}$) and vitamin E (436 $\mu\text{g}/100\text{ g}$) (Aakre et al., 2020). Furthermore, seafood contains essential minerals such as iodine, selenium, zinc, and iron, as well as bioactive compounds, including peptides, antioxidants, and trace elements. The nutrient composition of seafood varies among species, with fish, shellfish, and crustaceans each offering unique nutrient profiles.

Seafood is highly perishable due to its high water content, nutrient composition, and various indigenous enzymes that contribute to the deterioration of seafood products post-harvest, rendering them unfit for consumption (Boziaris & Parlapani, 2017). Microbial activity is a major contributor to seafood spoilage, with bacteria serving as the primary spoilage agents. Fig. 1 depicts a schematic representation of seafood spoilage and its controlling strategies. Gram-negative psychrotrophic bacteria, such as *Aeromonas* spp., *Pseudomonas* spp., and *Enterobacteriaceae* spp., thrive under chilled conditions and are primarily responsible for seafood spoilage (Anagnostopoulos, Parlapani, & Boziaris, 2022). The prevalence of lactic acid bacteria (LAB), *Brochothrix thermosphacta*, and *Photobacterium* has also been recognized as significant, particularly in fish stored in vacuum-sealed containers or modified atmosphere packaging (Anagnostopoulos et al., 2022). In addition, the microbiota profile of seafood typically exhibits higher levels of Gram-negative bacteria, such as *Enterobacteriaceae*, and LAB (Gram, 2009). The microbial profiles of fish and shellfish display comparable microbiota when analyzed using traditional microbiological methods (Gram, 2009). A study focusing on shrimp from the coastal regions of Central America found *Shewanella* to be the predominant species, while other bacteria such as *Pseudomonas*, LAB, *Acinetobacter*, and *Coryneforms* were less common (Benner, Staruszkiewicz, & Otwell, 2004). These bacteria produce compounds such as biogenic amines, sulfides, and ketones during protein degradation, contributing to off-flavors, odors, and discoloration of seafood (Boziaris & Parlapani, 2017). In addition to microbial activity, enzymatic reactions can further deteriorate seafood quality. For instance, melanosis in shrimp, mediated by polyphenol oxidase and catalyzed by endogenous enzymes, leads to undesirable changes in texture, flavor, and appearance (Malinowska-Panczyk & Kolodziejska, 2018). Given the highly perishable nature of seafood and the challenges posed by microbial spoilage and enzymatic degradation, the role of effective packaging becomes crucial in extending shelf life and maintaining product quality. Traditional plastic packaging, though widely used, raises environmental concerns, necessitating a shift toward sustainable alternatives. This need forms the basis for exploring biodegradable materials, which not only address environmental challenges but also offer functional benefits tailored to seafood preservation.

3. Biopolymer smart nano-packaging for seafood products

Food packaging plays a crucial role in the food industry by effectively storing food while maintaining its nutritional and sensory qualities. It not only prevents spoilage but also protects delicate bioactive compounds from adverse physical and environmental conditions (Shukla, Chaurasia, Younis, Qadri, Faridi, & Srivastava, 2019). Biodegradable materials, particularly biopolymers, are emerging as promising

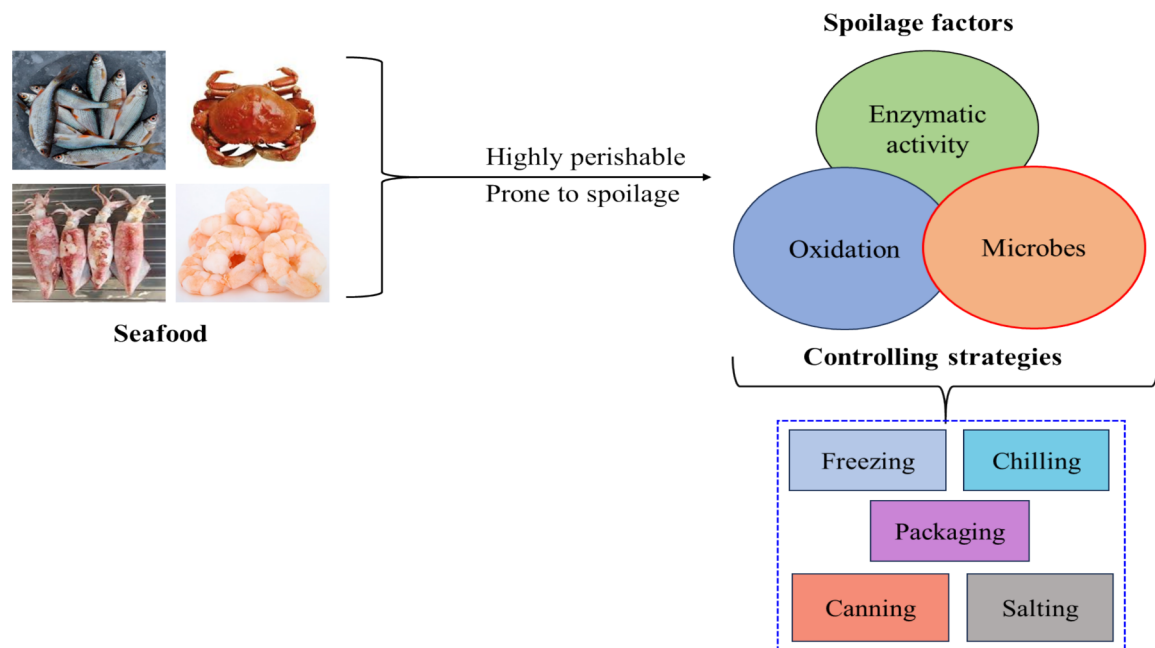


Fig. 1. Schematic representation of seafood spoilage and its controlling methods.

alternatives to conventional plastic packaging. Their ability to provide barrier properties, antimicrobial effects, and compatibility with nano-engineering innovations makes them suitable for addressing the unique preservation needs of seafood. Biodegradable packaging materials are primarily composed of biopolymers derived from natural sources, including carbohydrates, proteins, and lipids (Primožič et al., 2021). Carbohydrates, as a diverse group of compounds, include both simple sugars and complex polysaccharides. Among these, polysaccharides such as cellulose, starch, alginate, chitosan, pectin, and κ -carrageenan have been widely explored for their excellent film-forming properties, biodegradability, and functional versatility in packaging applications. Lipids, though less commonly used independently, are often incorporated into biopolymer composites to enhance moisture barrier

properties, making them particularly useful for packaging applications involving high-moisture foods such as seafood. An overview of biopolymer-based biodegradable smart nano-packaging is provided in the [Supplementary material](#). Smart packaging can be described as a combination of active and intelligent packaging systems. These materials are engineered to respond to specific stimuli, such as changes in pH, temperature, moisture, gas levels, light exposure, enzyme activity, or chemical composition (Sani, Azizi-Lalabadi, Tavassoli, Mohammadi, & McClements, 2021). They incorporate natural pigments that possess antioxidant and antimicrobial functions and exhibit tunable color profiles in response to these stimuli (Fig. 2). The use of these natural pigments, either individually or in combination within a biopolymer matrix, ensures safer packaging properties. These compounds can

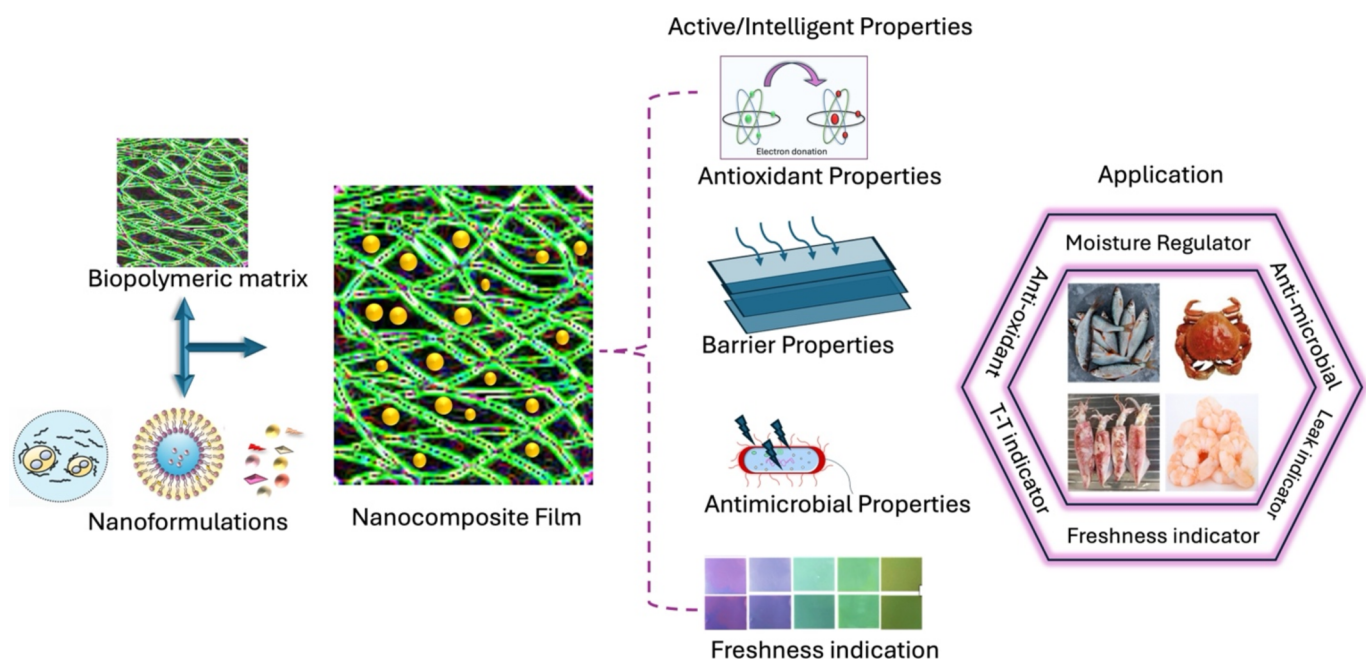


Fig. 2. Biodegradable nano-packaging incorporated with various bioactive materials or indicators for quality control of seafood products.

diffuse into the food, inhibit microbial growth, absorb gases (such as hydrogen sulfide, ammonia, and trimethylamine), and scavenge free radicals (Amin et al., 2022; Mohammadian, Alizadeh-Sani, & Jafari, 2020; Sae-leaw & Benjakul, 2019). Furthermore, incorporating functional compounds through nanotechnology—such as nanoparticles, nanospheres, and nanocolloids—enhances the functionality of smart packaging materials (Koirala et al., 2023).

3.1. Active packaging

Active packaging is defined as a packaging matrix that contains active substances, such as antimicrobials and antioxidants, which prevent food deterioration, extend shelf life, and improve the safety and sensory properties of food products (Pirsa et al., 2024b). Materials used for active food packaging are designed to possess functional attributes that go beyond the standard optical, mechanical, and barrier properties of conventional packaging materials (Ahmed et al., 2022). Active packaging typically performs several primary functions, including antibacterial activity, moisture regulation, ethanol release, CO₂ removal or release, ethylene absorption, odor adsorption, and deoxidation (Umair et al., 2023). Additionally, the stability and efficiency of active compounds within packaging materials can be enhanced through the integration of nanoengineering techniques.

3.1.1. Antioxidant properties

Marine fish and other seafood species contain abundant proteins and fats, which are highly susceptible to oxidation reactions — one of the leading causes of food spoilage. In addition to lipid oxidation, discoloration, melanosis, or black spot development in shrimp occurs due to the oxidation of tyrosine into quinones, mediated by polyphenol oxidase, even during cold storage (Nirmal & Benjakul, 2011). To mitigate the oxidation process, incorporating active components with potent antioxidant properties is essential. Plant extracts containing antioxidants, such as phenols, flavonoids, and essential oils (EOs), can effectively delay fatty acid oxidation and prevent chemical changes like melanosis (Kakadellis & Harris, 2020). Antioxidants typically inhibit oxidation by neutralizing singlet oxygen, reducing hydrogen peroxide, quenching free radicals, or chelating transition metal ions (Khajeh, Dashti-Khavidaki, Nasiri-Toosi, Mohammadi, & Jafari, 2019).

The nanosizing of antioxidant compounds enhances the entrapment efficiency, stability, and sustained release of antioxidants in packaging films. These enhancements depend on the incorporation matrix and the particle size of the entrapment medium (Sharma, Mulrey, Byrne, Jaiswal, & Jaiswal, 2022). Depending on the hydrophobicity or hydrophilicity of extracts and essential oils, different nanosystems can serve as carriers for antioxidant compounds, thereby improving the antioxidant potential of the packaging material (Acharya et al., 2024; Nie et al., 2023). For example, nanoemulsions, solid nanoparticles, nanoliposomes, and nanocapsules can be fabricated to entrap hydrophobic, hydrophilic, or both types of compounds (Ghiasi & Golmakani, 2023; Homayounpour, Shariatifar, & Alizadeh-Sani, 2021; Koirala et al., 2023). Nanoliposomes are metastable structures capable of encapsulating hydrophilic, hydrophobic, and amphiphilic compounds, providing gradual and controlled release properties. The protection of polyphenols from light and other environmental stimuli, along with their controlled release, enhances antioxidant activity (Aguilar-Pérez, Avilés-Castrillo, Medina, Parra-Saldivar, & Iqbal, 2020) and extends the shelf life of seafood. For instance, nanoliposomes incorporated with caraway seed extract demonstrated high antioxidant activity (Homayounpour et al., 2021). Solid lipid nanoparticles possess tunable surface properties, offering slower release and lower leakage rates of the entrapped compounds. Nanoemulsions, on the other hand, provide high active ingredient loading, controlled release, and minimal impact on the organoleptic properties of food, making them suitable for encapsulating antioxidative compounds (Ghiasi & Golmakani, 2023). Furthermore, certain biopolymeric nanoparticles exhibit antioxidant activity, high

food compatibility, and excellent encapsulation efficiency with controlled release properties (Koirala et al., 2023). Several studies have investigated the application of active packaging materials to prevent oxidation reactions in seafood products. Table 1 summarizes recent studies on different nanoformulations with natural antioxidants and biopolymers for seafood packaging. Hosseini, Ghaderi, & Gómez-Guillén (2022) explored the antioxidant effects of biopolymeric film made from cinnamon aldehyde-loaded chitosan nanoparticles on fresh rainbow trout fillets. The study concluded that the packaging film synergistically reduces secondary oxidation products due to the oxygen barrier properties of chitosan, the metal-chelating ability, and the electron-donating properties of cinnamon aldehyde. Candra et al. (2023) developed a high methoxyl pectin/gelatin/TiO₂ nanocomposite film containing curcumin, which protected salmon fillets from oxidative damage during refrigerated storage. This combination treatment extended the shelf life of salmon fillets by 12 days compared to control samples. Zhang, Gao, Jiang, & Xia (2023) created a novel bioactive packaging film using chitosan-lignin nanoparticles (LNPs) prepared with a deep eutectic solvent (DES). The film containing 1 wt% LNPs exhibited improved antioxidant and UV-blocking capacities. Yu et al. (2022) investigated an active packaging film made from chitosan loaded with proanthocyanidin nanoparticles (PC-NP) for preserving grass carp fillets during eight days of refrigerated storage. The film with 12–16 % PC-NP demonstrated over 90 % free radical scavenging activity, preventing protein and lipid oxidation and maintaining the texture of the fillets. Zhang et al. (2024) developed a nanocomposite film using a polyvinyl alcohol-chitosan blend incorporated with cinnamaldehyde-loaded zein-sodium alginate nanoparticles (ZCNPs). The film with 15 % ZCNP effectively reduced protein and lipid oxidation in silver pomfret (*Pampus argenteus*) during 12 days of refrigerated storage. Soltani, Kariminik, and Motaghi (2024) reported that a Persian gum-based nanocomposite film loaded with gliadin nanoparticles containing cinnamon essential oil extended the shelf life of rainbow trout fillets by reducing lipid and protein degradation during 12 days of refrigerated storage.

Overall, these studies indicate that biopolymer nanocomposites enhance the efficacy of bioactive compounds by stabilizing and protecting them under varying temperatures, light exposure, and adverse conditions. Furthermore, nanocomposites improve the mechanical and functional properties of packaging films, which can indirectly support and enhance the bioactive functions of the film.

3.1.2. Antimicrobial properties

Antimicrobial agents, such as plant extracts or phenolic compounds, can penetrate microbial membranes, disrupt membrane integrity, interact with cellular components, and alter metabolic pathways and genetic makeup. These actions result in the leakage of cellular contents and/or cell death (Lobiuc et al., 2023). Several natural antimicrobial agents have been investigated for potential incorporation into active packaging materials. Studies on the application of nanoengineered active packaging for seafood are summarized in Table 1. These findings indicate that smart nanopackaging films enriched with antimicrobial compounds have significant potential in next-generation seafood packaging (Al-Asmari et al., 2024). In a recent study, a nanoactive packaging film was developed using seaweed (*Gracilaria crassa*) extract (1 %), chitosan (1 g), and silver nanoparticles (Ponnusamy et al., 2024). This film was tested for quality control of shrimp nuggets stored at 4 °C for nine days. The packaged samples exhibited the lowest total plate count (TPC) (3.8 log CFU/g) compared to the control sample (5.7 log CFU/g) (Ponnusamy et al., 2024). The antimicrobial activity was attributed to the interaction between the positively charged polymer groups and the negatively charged microbial cell membranes (Shetta et al., 2024). Tang et al. (2023) utilized carboxymethyl cellulose and cobalt-based metal-organic frameworks to produce UV-blocking and antibacterial nanocrystals for shrimp packaging. The study found that bacterial cell membranes were severely damaged by cobalt ions released from the nanocrystals, resulting in bacterial death. Mohammadi, Mirabzadeh,

Table 1
Application of active biopolymer nanopackaging for seafood products.

Seafood Products	Type of nano-packaging	Active Additives	Additive Functions	Effects	References
Salmon (<i>S. salar</i>) fillets	Nano-composite (methoxyl pectin/gelatin/TiO ₂ composite film)	Curcumin	Antimicrobial	– TVC, PBC ↓ – Shelf life 12 days	(Candra et al., 2023)
Grass carp fillets	Chitosan-lignin nanoparticles composite film	Lignin nanoparticles	Antioxidant, and antibacterial	– TBARS ↓ – TVC ↓ – Shelf life 14 days	(Zhang et al., 2023)
Grass carp fillets	Chitosan- proanthocyanidins loaded nanoparticles	Proanthocyanidins	Antioxidant, antibacterial, and oxygen barrier	– TBARS ↓ – TVC ↓ – Shelf life 8 days	(Yu et al., 2022)
Rainbow trout (<i>O. mykiss</i>) fillets	Nanoparticles	Cinnamaldehyde	Antioxidant, Antimicrobial	– <i>Staphylococcus aureus</i> , <i>Listeria monocytogenes</i> , <i>Escherichia coli</i> and <i>Salmonella enteritidis</i> ↓ – TBARS ↓ – DPPH radical scavenging activity, FRAP ↑ – Shelf life 12 days	(Hosseini et al., 2022)
<i>Otolithes ruber</i> fillets	Nanocomposite (chitosan nanofiber + cinnamon essential oil in nanostructured)	<i>Zataria multiflora</i> Boiss essential oil	Antioxidant, Antimicrobial	– <i>Enterobacter aerogenes</i> , <i>Proteus mirabilis</i> , TVC, PVC, TBARS, TVB-N ↓ – Shelf life 15 days	(Mohammadi et al., 2023)
Silver pomfret	Polyvinyl alcohol/chitosan loaded with cinnamaldehyde incorporated zein nanoparticles	cinnamaldehyde	Antioxidant, antibacterial, and oxygen barrier	– TBARS ↓ – TVC ↓ – Shelf life 12 days	(Zhang et al., 2024)
Surimi	Nanocomposite	Turmeric essential oil	Antimicrobial	– <i>Bacillus cereus</i> ↓ – Shelf life 8 days	(Surendhiran, Roy, Park, & Chun, 2022)
Shrimp nuggets	Nanoparticle-inspired biodegradable film	Chitosan, seaweed extract, and silver nanoparticles	Antioxidant and antimicrobial	– TVB-N, TMA-N, FFA, PV, TBARS ↓ – TVC	(Ponnusamy et al., 2024)
Rainbow trout (<i>O. mykiss</i>) fillets	Persian gum-based bio-nanocomposite loaded with gliadin nanoparticles containing cinnamon essential oil	Cinnamon essential oil	Antioxidant and antimicrobial	– TVC, PBC ↓ – <i>P. fluorescens</i> , <i>A. hydrophila</i> , and <i>E.coli</i> ↓ – TVB-N, PV, and TBARS ↓ – Shelf life 12 days	(Soltani et al., 2024)

Shahvalizadeh, and Hamishehkar (2020) designed packaging films incorporating chitosan nanofibers and cinnamon essential oil (CEO) within nanostructured lipid carriers (NLCs). The film with nanostructured lipid carriers exhibited higher antimicrobial activity compared to films containing emulsified CEO. This was attributed to the sustained and controlled release of CEO from the nanostructures over time. Soltani et al. (2024) developed a Persian gum-based nanocomposite film incorporating gliadin nanoparticles loaded with cinnamon essential oil. The film with 10 % (w/w) CEO showed the highest encapsulation efficiency and improved mechanical properties. When applied to rainbow trout fillets, the film effectively reduced the total viable count, psychrotrophic bacteria, *Pseudomonas fluorescens*, *Aeromonas hydrophila*, and *Escherichia coli* over ten days of refrigerated storage. The antimicrobial activity was attributed to the sustained release of CEO during storage (Soltani et al., 2024). Zhang et al. (2024) investigated a polyvinyl alcohol (PVA)-chitosan active film incorporating cinnamaldehyde-loaded zein-sodium alginate nanoparticles (ZCNPs) for packaging silver pomfret (*Pampus argenteus*). The film with 15 % ZCNP exhibited a higher antimicrobial effect compared to lower doses, extending the shelf life of fillets by sustaining the release of cinnamaldehyde over 12 days of refrigerated storage (Zhang et al., 2024).

In another study, Zhang et al. (2023) developed a chitosan-lignin nanoparticle (LNP) film using a deep eutectic solvent (DES). The film containing 1 wt% LNPs inhibited foodborne pathogens such as *Staphylococcus aureus* and *Escherichia coli* through the inhibition zone method. When grass carp fillets were packaged with this film during 14 days of refrigerated storage, the total viable count (TVC), *Pseudomonas* count, and H₂S-producing bacteria count were significantly reduced compared to the control. While the control samples spoiled by day 5, the packaged samples remained consumable up to day 12, extending shelf life by five days (Zhang et al., 2023).

These studies suggest that the antimicrobial effect of active biopolymer films is attributed to the active compounds incorporated into the film via nanoengineering. The sustained release of these active compounds during storage effectively inhibits microbial proliferation. Additionally, the water resistance and oxygen barrier properties of the active film work synergistically to reduce microbial growth (Zhang et al., 2023).

3.1.3. Moisture regulators

Moisture-regulating biodegradable packaging materials help prevent excess moisture accumulation within packages, thereby reducing the

risk of food spoilage (Erfani et al., 2023; Dadkhah et al., 2024)). Biopolymers can be modified using nanoengineering to achieve the desired polarity for effective moisture regulation. Either used individually or in combination, these biopolymers possess high moisture absorption capabilities, which aid in controlling the moisture content of seafood and preserving its quality (Perera, Jaiswal, & Jaiswal, 2023; Shankar & Jaiswal, 2024). For instance, carboxymethyl cellulose (CMC) exhibits significant moisture absorption ability, with the absorption rate influenced by its concentration (Pirsa et al., 2024a). CMC also demonstrates excellent moisture permeability, as reported by Yaradoddi et al. (2020) and Bajpai, Chand, and Ahuja (2015). The surface hydroxyl groups of CMC readily attract water molecules, making the CMC composite film hygroscopic. When water vapor enters the film matrix, the fluorene groups in the cellulose chain do not interact with the invading water molecules due to strong internal triple-bond interactions, resulting in good moisture permeability (Bajpai et al., 2015).

Nanoparticles and nanomaterials in packaging can fine-tune the moisture-regulating properties of packaging films (Pirsa et al., 2020). The addition of nanofillers decreases the solubility of biopolymer films, improves their swelling degree, and increases water resistance. These improvements are attributed to the aspect ratio of nanoparticles, the presence of crystalline regions, the strengthening of irregular polymeric chains, and strong hydrogen interactions (Jamroz, Kulawik, & Kopel, 2019). Gan, Sam, Abdullah, Omar, and Tan (2021) documented that incorporating nanocrystalline cellulose into a chitosan matrix reduces water vapor permeability, solubility, and swelling properties. This phenomenon occurs because the mobility of biopolymer chains is hindered by impermeable nanoparticles within the biopolymer matrix, thereby lowering the water vapor permeability of the nanocomposite films (Bahrami, Rezaei Mokarram, Sowti Khiabani, Ghanbarzadeh, & Salehi, 2019). However, some studies have reported the opposite trend, where adding nanoparticles increases the swelling degree and water vapor permeability (WVP) of the film. For example, increasing concentrations of silver nanoparticles in chitosan/alginate films led to higher swelling and WVP. This effect is due to the nanoparticles' ability to bind water molecules and form hollow structures by interacting with polyelectrolytes (Susilowati, Masykuri, & Hastuti, 2020). Therefore, selecting the appropriate nanoformulation and optimizing its concentration is crucial to achieving the desired moisture-regulating properties. Zhang et al. (2023) investigated the effect of lignin nanoparticles (LNP) on chitosan-based packaging films. Films incorporating 1 % LNP exhibited reduced swelling and lower water vapor transmittance. Grass carp fillets packed with these films showed less water loss and fewer biochemical changes, such as lipid oxidation and microbial contamination. These benefits were attributed to the synergistic effect of the active compounds and the film's moisture barrier properties (Zhang et al., 2023). In another study, Zhang et al. (2024) reported that the addition of cinnamaldehyde-loaded zein nanoparticles (ZCNP) to polyvinyl alcohol (PVA)/chitosan films improved water resistance, oxygen barrier properties, and mechanical strength. When silver pomfret fillets were packaged with these films, oxidation and microbial proliferation were significantly reduced. This effect was due to the active compounds and the enhanced water vapor transmittance barrier properties of the film (Zhang et al., 2024).

The results indicated that the addition of nanofillers to biopolymer composites enhances the film's water resistance by reducing its water vapor permeability. Furthermore, the uniform distribution of nanoparticles within the biopolymer matrix creates a more compact structure, restricting the movement of water molecules (Zhang et al., 2023; Zhang et al., 2024).

3.2. Intelligent packaging

Intelligent packaging consists of sensors and detectors. Sensors are employed to detect physical, biological, and chemical changes, while detectors provide information about product quality, environmental

conditions, and food-related gases (Müller & Schmid, 2019). Currently, both synthetic dyes (e.g., phenol red, methyl red, chlorophenol red, methyl orange, and dimethyl yellow) (Zhang & Lim, 2018) and natural dyes (e.g., anthocyanins, betalains, carotenoids, anthraquinones, chlorophylls, and curcumin) (Ekrem Parlak et al., 2024) are being studied for their potential use as sensing materials in food spoilage indicators (Table 2). However, the direct incorporation of these dyes into polymeric matrices has shown certain drawbacks, such as sensitivity to light (Ghiasi & Golmakani, 2023). Nanoengineering technology offers an effective approach to overcoming these challenges by improving the stability and functionality of such indicators in biodegradable film matrices (Nirmal et al., 2024).

3.2.1. Freshness indicator

The freshness of seafood is lost upon spoilage, which can occur due to self-decomposition by enzymes, oxidative degradation, or microbial activity. During microbial growth and chemical changes, various metabolites such as CO₂, organic acids, volatile bases, and sulfur derivatives are released. These metabolites can react with pH-sensitive dyes, including anthocyanin, curcumin, betalains, methyl red, and bromothymol blue, incorporated into smart films to indicate freshness through colorimetric changes (Ekrem Parlak et al., 2024). For instance, trimethylamine is produced when bacteria break down trimethylamine oxide, a naturally occurring compound in marine species (Laorenza et al., 2022). Additionally, proteins containing amines break down to form biogenic amines like putrescine, cadaverine, and histamine, which are indicators of food spoilage and, inversely, of freshness (Kuswandi & Nurfawaidi, 2017). As spoilage progresses, the concentration of these metabolites increases, resulting in changes in pH or gas composition within the headspace of the seafood package (Kim, Lee, Lee, Baek, & Seo, 2017). You et al. (2022) developed a κ -carrageenan film loaded with anthocyanin and silver nanoparticles. The film exhibited excellent color stability under UV exposure and maintained stability at 25 °C for up to 240 days. When seabass fillets (50 g) were stored in a PET box with an indicator film (1.5 × 1.5 cm) at 4 °C for five days, the film changed color from purple to blackish-purple by day three, correlating with a total volatile basic nitrogen (TVB-N) level exceeding 30 mg/100 g (You et al., 2022). Likewise, Kim et al. (2022) evaluated a gelatin/agar film containing anthocyanin and ZnO nanoparticles for monitoring shrimp freshness during refrigerated storage. The color changes of the film correlated with increasing TVB-N levels, indicating shrimp quality deterioration (Kim et al., 2022). In another study, Yao, Yun, Xu, Chen, and Liu (2022) developed a double-layer locust bean gum/PVA and agar/PVA film incorporating red pitaya betacyanins and titanium dioxide nanoparticles. This film exhibited UV barrier properties, antioxidant and antimicrobial activity, and high sensitivity to pH changes and volatile compounds. When used with shrimp, the indicator film changed color from red-violet to dark red at 16 h, pink at 24 h, and brown at 48 h (Yao et al., 2022). Alizadeh Sani et al. (2022) created a green halochromic smart packaging film from a gelatin/ κ -carrageenan composite containing TiO₂ nanoparticles and anthocyanin from saffron and barberry. The film demonstrated stability under UV light and different storage temperatures, as well as water resistance and bioactivity. Trout fillets stored with this indicator film for 72 h at room temperature showed color changes due to ammonia gas formation, indicating spoilage (Alizadeh Sani et al., 2022). In another study, Zhang et al. (2023) prepared a bilayer sensor from agar, TiO₂ nanoparticles, and butterfly pea flower anthocyanin in a κ -carrageenan composite for monitoring *Penaeus chinensis* freshness. During four days of refrigerated storage, the sensor displayed color changes from blue to yellow-green, correlating with shrimp freshness (Zhang et al., 2023). Recently, Du, Said, and Lee (2024) developed a pH-sensitive film from dragon fruit peel pectin, betacyanin, sodium alginate, and TiO₂ nanoparticles. The film showed photostability, good mechanical properties, and water and oxygen barrier abilities. Mackerel fillets stored with this film exhibited color changes from reddish-violet to brownish-yellow at 4 °C and 25 °C,

Table 2

Application of intelligent biopolymer nanopackaging for seafood products.

Seafood product	Type of nano-packaging	Sensor/Indicator	outcome	references
Freshness indicator				
Seabass fillet	κ -carrageenan, Silver nanoparticle and red grape skin anthocyanin composite	Colorimetric: anthocyanin	<ul style="list-style-type: none"> – Enhanced UV-blocking ability – Sensitivity to pH and TVB-N changes – Strong antioxidant and antimicrobial activities – Freshness indicator changes color from purple to blackish purple 	(You et al., 2022)
Shrimp	Gelatin/agar incorporated with zinc oxide nanoparticles and <i>Clitoria ternatea</i> flower anthocyanin	Colorimetric: anthocyanin	<ul style="list-style-type: none"> – UV barrier property – Sensitivity to pH and TVB-N changes – Strong antioxidant and antimicrobial activities – Freshness indicator changes color from pink to green 	(Kim et al., 2022)
Shrimp	Double-layer locust bean gum/PVA and agar/PVA film containing red pitaya betacyanins and titanium dioxide nanoparticles	Colorimetric: Betacyanin	<ul style="list-style-type: none"> – UV barrier ability and mechanical properties – Sensitivity to pH and TVB-N changes – Strong antioxidant and antimicrobial activities – Freshness indicator changes color from red-violet to brown 	(Yao et al., 2022)
Trout fish	Gelatin/ κ -carrageenan composite incorporated with TiO ₂ nanoparticle and anthocyanin	Colorimetric: Saffron anthocyanin and barberry anthocyanin	<ul style="list-style-type: none"> – UV and water barrier properties – Sensitivity to pH and TVB-N changes – Strong antioxidant and antimicrobial activities – Freshness indicator changes Saffron anthocyanin color from violet to green and barberry anthocyanin color from pale peach to yellow 	(Alizadeh Sani et al., 2022)
<i>Penaues chinensis</i>	Agar/TiO ₂ nanoparticle/butterfly bean flower anthocyanin/ κ -carrageenan composite	Colorimetric: anthocyanin	<ul style="list-style-type: none"> – Photostability and low water vapor permeability – Sensitivity to pH and TVB-N changes – Strong antioxidant and antimicrobial activities – Freshness indicator anthocyanin color from blue to yellow-green 	(Zhang et al., 2023)
Mackerel fish fillet	Dragon fruit pectin/sodium alginate/TiO ₂ nanoparticles/betacyanin from dragon fruit peel	Colorimetric: betacyanin	<ul style="list-style-type: none"> – Photostability and water vapor and oxygen barrier properties – Sensitivity to pH and TVB-N changes – Freshness indicator betacyanin color from reddish-violet to brownish-yellow 	(Du et al., 2024)
Atlantic salmon fillet	Sodium alginate loaded with gold nanoparticles	Colorimetric: gold nanoparticle colloidal suspension	<ul style="list-style-type: none"> – Strong antimicrobial activities – Sensitivity to pH and TVB-N changes – Freshness indicator betacyanin color from red to green 	(Pierre et al., 2024)
Bighead carp head	PVA-based film incorporated with anthocyanin-encapsulated whey protein-propylene glycol alginate nanoparticle	Colorimetric: anthocyanin	<ul style="list-style-type: none"> – UV and water barrier properties – Sensitivity to pH and TVB-N changes – Strong antioxidant activity – Color stability at 4 and 25 °C – Freshness indicator changes color from rosy red to gray 	(Lv et al., 2024)
Time-temperature indicator				
Fresh food	Carboxymethyl cellulose incorporated with polydiacetylene-silver nanocomposite	TTI: Total color difference	<ul style="list-style-type: none"> – Color change from purplish blue to reddish-purple in response to storage at 35 °C for 14 days 	(Saenjaiban et al., 2020)
Fresh food	Carboxymethyl cellulose, PVA, and chitosan incorporated with polydiacetylene- silver nanocomposite	TTI: Total color difference	<ul style="list-style-type: none"> – Color change from blue to reddish-purple in response to storage at 35 °C for 14 days. 	(Saenjaiban et al., 2024)

indicating spoilage due to ammonia and trimethylamine formation (Du et al., 2024). Pierre et al. (2024) developed a colorimetric indicator using gold nanoparticles and sodium alginate for evaluating fish freshness. The indicator responded to pH and TVB-N levels, changing color from red to green. When used with Atlantic salmon fillets during nine days of refrigerated storage, the indicator effectively tracked TVB-N fluctuations (Pierre et al., 2024). Lv et al. (2024) fabricated a freshness indicator film from a PVA matrix loaded with anthocyanin encapsulated in whey protein-propylene glycol alginate nanoparticles. This

film exhibited high water resistance, oxygen barrier properties, UV-blocking ability, and color stability at various temperatures. When applied to bighead carp heads stored at 4 °C and 25 °C, the film color changed from rosy red to gray, indicating spoilage.

These studies indicate that pH-sensitive films made from composites of nanoparticles and natural colorants exhibit enhanced photostability, water vapor and oxygen barrier properties, and bioactivity. Most importantly, these films demonstrate excellent color stability during storage. Furthermore, their sensitivity to pH changes or volatile gas

formation (e.g., ammonia, trimethylamine) allows them to effectively indicate changes in the freshness quality of seafood products.

3.2.2. Time-temperature indicator

These indicators provide consumers with insight into whether a product has been exposed to inappropriate temperatures. Packaging incorporating these indicators undergoes an irreversible color change when subjected to unsuitable temperatures. The increasing acidity in the food matrix at elevated temperatures can be detected via the film's color change. [Pereira, de Arruda, and Stefani \(2015\)](#) designed a polyvinyl alcohol (PVA)/chitosan-based colorimetric film doped with anthocyanin to detect temperature changes in food. The color shift in the film upon exposure to higher temperatures provides a visual indication of temperature fluctuations. The time-temperature indicator effect achieved through color changes in myoglobin and myoglobin-nitrite proteins was studied by [Santos, Veiga-Santos, Sestari, Sorrini, and de Oliveira Roça \(2020\)](#). Their research demonstrated significant changes in chroma after 60 min of exposure at 100 °C and 170 °C, showing that both temperature and nitrite concentrations affected the intensity of the red color. Polydiacetylene-silver nanoparticles incorporated into carboxymethyl cellulose-based sensors have also been investigated for their potential use as temperature indicators ([Saenjaiban, Singtisan, Suppakul, Jantanasakulwong, Punyodom, & Rachtanapun, 2020](#)). Polydiacetylene self-assembles into vesicles or conjugates with a polymer backbone via 1,4-addition polymerization of diacetylene monomers, alternating between C=C and C≡C bonds. This structural alteration results in a color change from colorless to blue ([Saenjaiban et al., 2020](#)). Recently, [Saenjaiban et al. \(2024\)](#) developed biopolymer films consisting of carboxymethyl cellulose, PVA, and chitosan, incorporated with a polydiacetylene-silver nanocomposite as a time-temperature indicator for fresh products. The developed film changed color in response to temperatures of 35 °C over 14 days of storage. Specifically, the film changed from blue to reddish-purple and reddish-brown for chitosan- and PVA-based films, respectively. In real-time detection, gases such as ammonia (NH₃) accumulate in seafood products as storage time increases. Films that change color in response to higher concentrations of such gases can be used as effective freshness indicators. Additionally, the respiration rate of the food sample can be determined using non-destructive visual oxygen and carbon dioxide sensors to measure gas content within the packaging ([Kalpana, Priyadarshini, Maria Leena, Moses, & Anandharamakrishnan, 2019](#); [Shao et al., 2021](#)). These sensors provide real-time spoilage detection of packaged products.

4. Challenges and future directions in biopolymer smart nanopackaging applications

The development of smart nanopackaging has the potential to significantly advance seafood packaging; however, several challenges remain. These challenges include: 1) Consistency and Reproducibility – Ensuring the consistency and reproducibility of nanocomposites used in biopolymer packaging, as well as maintaining the stability of these composites under various storage conditions. 2) Impact of Nano-Formulation Methods – Understanding how different nano-formulation methods—whether physical, chemical, or enzymatic—affect the mechanical and functional properties of nanopackaging. 3) Scaling Up Production – Scaling up biopolymer nanopackaging for seafood applications may require the installation of entirely new equipment, replacing existing infrastructure. This presents a significant challenge for the seafood industry. Additionally, an in-depth study of the flow dynamics of coating and packaging formulations is necessary. 4) Cost Considerations – Functionalization and nanoengineering approaches may increase the overall cost of packaging materials, thereby raising the cost of seafood products. 5) Consumer Safety and Acceptance – Addressing consumer safety, perception, and acceptance of nanopackaging materials is critical and requires comprehensive studies. 6) Integration and Environmental Impact – Multiple factors must be considered, including

the integration of active compounds, cost-benefit analysis, and potential health and environmental concerns.

Further exploration of novel biopolymers and nanocomposites for smart film fabrication could lead to the development of advanced packaging materials with smart features, addressing the limitations of currently available biopolymers. However, the indiscriminate use of bioactive ingredients to achieve specific film properties can introduce potential hazards, such as the migration of nanomaterials into the food matrix and the resulting cytotoxicity. Comprehensive studies on the migration of nanomaterials and active compounds, as well as their interactions with human biology, are essential for the industrial application of smart nanopackaging. Uncertainty regarding cytotoxicity and the lack of adequate risk assessment research remain significant barriers to the commercial adoption of smart nanopackaging. Another challenge associated with seafood wrapped in nanoformulations containing compounds like essential oils is their potential negative impact on the sensory attributes of the seafood. To enhance consumer acceptance, it is advisable to use appropriate concentrations of bioactive compounds, optimize nanometric transformations, and incorporate complementary constituents. These strategies could facilitate the replacement of synthetic packaging materials in the seafood industry. Moreover, overcoming the challenges in the biopolymer nano-packaging market requires multidisciplinary research involving experts in food and packaging engineering, materials science, and marine science. Collaborative efforts in these fields are crucial to advancing the development of smart nanopackaging and supporting the growth of the global seafood industry.

5. Conclusion

In the contemporary world, technologically advanced food packaging is highly valued for its contribution to environmental sustainability. Over the past two decades, extensive research has explored sustainable biomaterial alternatives to plastics for food preservation applications. Smart biopolymer packaging offers promising solutions to mitigate the environmental concerns associated with conventional plastic packaging. Nanostructures have also garnered significant attention due to their potential to enhance the functional properties of packaging films, such as antimicrobial activity, antioxidant capacity, moisture regulation, and freshness indication. Incorporating nanotechnology into biopolymer packaging imparts advanced features, including temperature, pH, and freshness monitoring, which can effectively detect seafood spoilage. However, several challenges remain and require careful consideration. These include the need for exploring novel biomaterials, conducting detailed studies on the cytotoxicity of nanomaterials, and addressing the scalability of smart nanopackaging films for industrial applications. Overcoming these gaps is essential for realizing the full potential of smart nanopackaging in promoting sustainable food preservation.

CRediT authorship contribution statement

Pankaj Koirala: Resources, Data curation, Investigation, Writing – original draft. **Narashans Alok Sagar:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Arthittaya Thuanthong:** Data curation, Writing – original draft. **Fahad Al-Asmari:** Data curation, Writing – original draft. **San-deep Jagtap:** Visualization, Writing – review & editing. **Nilesh Nirmal:** Conceptualization, Project administration, Supervision, Validation, Resources, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.foodres.2025.115826>.

Data availability

Data will be made available on request.

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Revolutionizing seafood packaging: advancements in biopolymer smart nano-packaging for extended shelf-life and quality assurance

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