**Nano Packaging of Seafood: Applications, Challenges, and Future Perspectives**

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**Abstract:**

Seafood is a highly perishable commodity that requires effective packaging solutions to maintain its quality and safety during storage and transportation. In recent years, nanotechnology has emerged as a promising approach for developing innovative packaging materials with enhanced functional properties. Nano packaging of seafood involves the use of nanomaterials such as nanoparticles, nanofibers, and nanocomposites to improve the shelf-life, sensory quality, and safety of seafood products. This book chapter provides a comprehensive overview of the applications of nanotechnology in seafood packaging, including the use of nanosensors, nanocoatings, and nanoencapsulation. The chapter discusses the potential benefits of nano packaging of seafood, such as improved barrier properties, antimicrobial activity, and sensory attributes. However, the use of nanomaterials in food packaging also poses certain challenges and concerns, such as the potential migration of nanoparticles into food, toxicity issues, and regulatory hurdles. Therefore, the chapter also addresses the safety and regulatory aspects of nano packaging of seafood. Overall, this book chapter offers valuable insights into the potential applications and challenges of nanotechnology in seafood packaging, and highlights the need for further research to ensure the safety and sustainability of nano packaging materials.

**Key words:** Food safety, Nano Packaging, Nanomaterials, Seafood, Shelf life.

1. **Introduction**

 The Indian fishing industry is one of India's fastest-growing economic sectors, contributing 1.29% of the country's national GDP and 7.9% to agricultural GDP. During the year 2021-22, India has exported 13,69,264 MT of seafood worth Rs 57,720.98 crore (US$ 7.46 billion). The seafood export during the year has increased by 31.71% in rupee value terms, 30.26% in US dollar value terms and 19.12% in quantity terms. USA, China and European Union (EU) are the major importers of Indian seafood [[1](#one)]. Considering the per capita consumption of world, it has increased from a 9 kg in 1961 to 20.2 kg in 2020 and estimated to reach 21.4 kg by 2030 [[2](#two)]. In India, per capita fish consumption of fish is estimated at 5-6 kg whereas for the fish-eating population it is found to be 8-9 kg [[3](#three)].

Today, one of the most important problems of our world, which is in a rapid change in social, economic and cultural terms, is nutrition with adequate, balanced and healthy foods. Among seafood, edible fishes and crustaceans such are prawn, shrimp, crab and lobster which constitutes the one of the important nutritious food sources for human being. Seafood is one of the important sources for food, nutrition, livelihood, and income and has been recommended to be consumed more frequently by nutritionists and health experts [[4](#four)]. Seafood is rich in essential amino acids, minerals, vitamins, antioxidants, and mono and polyunsaturated fatty acids that are crucial for human health [[5](#five)]. In addition, they are particularly rich in docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), which are polyunsaturated fatty acids that are exclusively found in all seafood and not in other food sources [[6](#six)].

However, seafood contains high moisture content, neutral pH, resident microbes, it begins to decay after harvesting even through these health advantages. Their sensory and nutritional qualities changed as a result of these enzymatic and oxidative reaction processes. Consumers do not view the alteration as a decrease in the quality of freshness, which shorten their shelf life. Additional factors contributing to the rapid deterioration of seafood products include storage conditions, atmospheric oxygen, reduction-oxidation reactions, non-protein nitrogenous compounds, and the presence of trimethylamine oxide (TMAO) [[7](#seven)]. Therefore, in order to maintain food safety and quality, the cold chain must remain linked during transportation, storage, and distribution of seafood products.

In recent years, changes in consumer preferences and the needs of the food industry have more focus on developing packaging technologies that can improve food safety and functionality [[8](#eight)]. Until now, various packaging technologies have been developed, such as modified atmosphere packaging (MAP), smart packaging systems, active packaging systems, and edible film coatings, which have been used to preserve food quality and extend shelf life [[9](#nine)-[12](#twelve)]. These packaging techniques with nanotechnological applications have also been for packaging fish and shellfish products. Nanotechnology is a field of science that focuses on the investigation of materials that have a size range of one nanometer, which is equivalent to one billionth of a meter or utilized one millionth of a millimeter. This field involves the examination, control, and development of new properties, production, characterization, and application of materials at the nanoscale. Materials with dimensions ranging from 1 to 100 nanometers are considered as nanomaterials and are broadly categorized as organic-based (carbon-based), inorganic-based (metal and metal oxide-based), or hybrid materials based on their structural composition [[13](#thirteen)].

The field of nanotechnology has introduced novel advancements to the technology of food packaging and increase the performance of packaging (Figure 1). Nanoparticles are incorporated into packaging materials to enhance their barrier and mechanical properties, as well as develop biodegradable and active packaging systems. In addition, nanosensors are produced, which have led to the development of smart packaging applications that use these sensors. (Figure 2). These innovations have paved the way for efficient and sustainable food packaging solutions. are produced, which have led to the development of smart packaging applications that use these sensors. (Figure 2). These innovations have paved the way for efficient and sustainable food packaging solutions.



***Figure 1. Nanotechnological Applications in Food Packaging***



***Figure 2. Nanoparticles Used in Food Packaging***

**2.0. Nanomaterial based physically and mechanically improved packaging**

**2.1. Usage in Synthetic Polymer Based Packaging**

The use of polymer-based films in the packaging of foods is quite common. Polymers are higher molecular weight compounds formed by the regular bonding of many chemical molecules. About 5% of the oil processed in the world is used in the polymer industry. Petroleum is used as a source in the production of many synthetic polymers. The superior mechanical and thermal properties of polymers have made them the preferred product in many areas of the industry. Polypropylene (P.P.), polyethylene (HDPE, LDPE, etc.), polyethylene terephthalate (PET), polystyrene (P.S.), and polyvinyl chloride (PVC) are among the most used polymers in food packaging, and these different polymers exhibit different barrier properties. For example, polyethylene terephthalate (PET) provides a better barrier against oxygen than high-density polyethylene (HDPE), while HDPE provides a better barrier against water vapor than PET [[14](#fourteen)].

In order to improve the barrier properties of polymer-based packaging materials or to give them different properties, nanoparticles are added to these materials, or composite materials are produced. Composite is a material that consists of two or more components. The use of nanoparticles and nanocomposites in food packaging has also started to gain importance. Nanocomposite packages are polymers containing organic or inorganic-based nanoparticles. The barrier properties of a polymer are affected by many factors such as the degree of branching, hydrogen bonding, polarity, cross-linking, and crystallinity. Nanoparticles added as filler to polymer nanocomposites create an important barrier that will prevent both oxygens, carbon dioxide, and humidity from passing into the food and ensure that the material is light, tearproof, and high temperature resistant. Clay and silicate nanoplatelets silica nanoparticles are most commonly used as filling materials [[15](#fifteen), [16](#seventeen)].

The fact that clay and silicate materials are durable, non-toxic by nature, and available at low prices makes them preferred as fillers. Because of these properties, nanoclay-based polymer is used in food packaging industry. Nanoclay applications to polymers such as montmorillonite, kaolinite, hectrite, and saponite have been widely studied [[17](#seventeen)]. By incorporating the nanoclay particle into the polymer matrix, the moisture stability of the film is increased, and the oxygen permeability is reduced. In addition, when the surface of a very small amount of nano-sized clay particles is wrapped with polymer, it shows strong barrier properties against oxygen and moisture and shows high thermal resistance. Jung et al. [[18](#eighteen)] reported that polypropylene (P.P.) packaging material containing clay and hollow glass microspheres reduces oxygen permeability by 32%. In addition, talc nanoparticles added to polypropylene-based films increase tensile strength and impact strength by 226% and 166%, respectively [[19](#nineteen)]. Furthermore, MMT-based composite inclusion in laminated clay/polyvinyl alcohol films reduces oxygen permeability, prolongs the retention time of hydrophilic and lipophilic antioxidants, and delays discoloration [[20](#twenty)]. Particular in seafood, Khanipour et al. [[21](#twentyone)] produced a low-density polyethylene composite film containing 5% clay nanoparticles to package rainbow trout (*Oncorhynchus mykiss*) fillets. After storage, the shelf life of the experimental samples was found to be 18-20 days, which is longer than that of the control samples (13-15 days).

**2.2. Usage in Biopolymer Based Packaging (Bionanocomposites)**

Biopolymers are a type of polymer that can be decomposed by microorganisms in the natural environment, making them environmentally friendly and sustainable. Due to the negative impact of petroleum-based plastics on the environment and ecology, biodegradable polymers have been widely used in food packaging. Biopolymers can be derived from natural or synthetic sources, such as polysaccharides, proteins, and polyhydroxyalkanoates (PHA) [[22](#twentytwo), [23](#twentythree)].

Although the film-forming ability of biopolymers is good, their mechanical and water vapor barrier properties are relatively low compared to petroleum-based polymers [[24](#twentyfour),[25](#twentyfive)]. To address this issue, studies on nanotechnological applications have been conducted to enhance the properties of biopolymer films by incorporating nanoscale particles into polymeric matrices [[22](#twentytwo)]. Clay particles have been widely used in the enhancement of biopolymer films. For example, adding layered silicates to gelatin-based biopolymer films can improve their barrier and mechanical properties [[22](#twentytwo)].

Incorporating nanoclay particles into the gelatin matrix can also increase the strength of the nanoclay/gelatin nanocomposite film, decrease water vapor permeability and light transmission, and provide positive physical and mechanical properties to the gelatin film [[25](#twentyfive)]. Fish gelatin and nanoclays have been used to prepare nanocomposites with improved mechanical and water barrier properties [[26](#twentysix)]. PLA nanocomposite films embedded with unmodified montmorillonite (MMT) clay have been found to delay lipid oxidation of fatty foods due to their enhanced water barrier properties, thereby extending the shelf life of fatty foods [[27](#twentyseven)]. Additionally, the use of clay-containing coatings has been shown to improve the sensory quality of shrimp samples during the cold storage period and delay lipid oxidation and discoloration [[28](#twentyeight)].

**3.0. Use of Nanotechnology Based Active Packaging Systems**

Nanotechnology is an increasingly popular method for enhancing the effectiveness of active packaging systems. The adding of nano components with antimicrobial and oxygen scavenging properties to the packaging material or using metal oxides and nanoclays to create an enzyme immobilization system is mostly prevalent.

In active antimicrobial packaging, metal nanoparticles such as silver, gold, zinc, copper, silver-zeolite, silver-gold, and titanium dioxide (TiO2), zinc oxide (ZnO), silicon dioxide (SiO2), and magnesium oxide are preferred due to their small size and surface reactivity properties. Furthermore, Enescu et al. [[29](#twentynine)] have conducted research on the use of different enzymes, bacteriocins, essential oils, anhydrides, and weak organic acids in seafood and other foodstuffs to increase antimicrobial activity with active nanocomponents. This research highlights the potential of using a variety of active ingredients in active packaging systems to improve their effectiveness in preserving food products.

The use of antimicrobial nanoparticles in active seafood packaging is a broad research topic. Singh et al. [[30](#thirty)] prepared polypropylene films containing 5% and 10% silver silica and compared their antimicrobial properties to a control sample. The composite film preserved the quality of raw mullet (chub mackerel) for 7 days at +2 oC, as indicated by low thiobarbituric acid (TBA) values and no increase in trimethylamine (TMA), which causes fishy odors. *Psychrophilic* microorganism growth was also reduced in the composite. Efatian et al. [[31](#thirtyone)] tested nanocomposite films containing LDPE/Ag/TiO2 and LDPE/Ag+Cu/TiO2 for antibacterial activity during Nile Tilapia storage at +4 oC and -20 oC. The Ag+Cu-containing film had higher antimicrobial activity, and nanoparticle migration was < 2.0 µg/kg and < 10 µg/kg, respectively. Paidari et al. [[32](#thirtytwo)] found that nanoclay and nanosilver in LDPE polymer had a synergistic effect against *Vibrio parahaemolyticus*, *Escherichia coli*, and *Staphylococcus aureus* in shrimp samples. However, the effectiveness of nanocomposites decreased after the shelf-life period. Esmailzadeh et al. [[33](#thirtythree)] compared the antibacterial activities of CuO/LDPE and ZnO/LDPE nanocomposites and reported that both nanoparticles were effective in active packaging against spoilage bacteria, with a slight difference in effectiveness.

**4.0. Nanotechnological Based Intelligent/Smart Packaging Systems**

Smart packaging systems are designed to provide a specific indicator of chemical, enzymatic, microbial changes or changes in storage conditions in the packaged food. This provides traceability of food quality with the naked eye without harming the packaging integrity [[34](#thirtyfour),[35](#thirtyfive)].

In this system, indicators and nanosensors are applications that provide technological support. Indicators used in packaging are grouped as oxygen indicators, deterioration and contamination indicators, time, temperature, humidity indicators, and freshness indicators. Nanosensors are used in pathogen detection, gas detection, aroma detection, freshness detection of processed products, flavor detection, food pollutants, or toxin detection [[36](#thirtysix)]. The combined use of nano-active materials and nanocomposites has found a place in smart packaging systems as well as in active packaging systems and has provided a strengthening effect to smart packaging.

Freshness indicators are one of the smart packaging system applications that have been extensively studied. These indicators have been applied to nano packages. Among these indicators, pH colorimetric indicators have received wide attention. pH change often accompanies the food spoilage process, and these indicators provide measurability when there is a significant change in the pH of packaged food [[10](#ten), [34](#thirtyfour)]. Ge et al. [[10](#ten)] prepared a pH-sensitive colorimetric film for monitoring the freshness of shrimp and hairtail by incorporating chitin nanocrystals and black rice bran anthocyanins into a gelatin matrix. The color of the films changed from purple to gray-blue or brown due to the increase in TVB-N levels during storage. Wu et al. [[37](#thirtyseven)] also developed a smart film with pH sensitivity and UV barrier properties by incorporating black rice bran anthocyanins into a chitin nanocrystals/chitosan matrix. The films containing 3% anthocyanins could monitor the degradation of fish and shrimp with visible color changes, but the mechanical and barrier properties were reduced. Alizadeh-Sani et al. [[34](#thirtyfour)] reported that adding anthocyanin to the pH-sensitive color indicator film they prepared using anthocyanin from the rubella plant increased its mechanical and water barrier properties and exhibited antioxidant activity. Naghdi et al. [[38](#thirtyeight)] developed a starch/betocyanin package label for monitoring the freshness of fish during storage, with the color changing from pink to yellow as TVB-N levels increased.

Metal/metal oxide nanoparticles have been studied as pH indicators, and it has been found that they exhibit a distinct color change with pH variation. AuNPs have been used by Lapenna et al. [[39](#thirtynine)] to detect biogenic amines, where a color change from burgundy to gray/blue occurred due to the aggregation of AuNP on biogenic amines. Zhai et al. [[40](#forty)] developed a colorimetric H2S sensing sensor based on AgNPs to detect degradation in silver carp. The biosensor developed by Mustafa et al. [[41](#fortyone)] used cerium nanoparticles as a chromogenic indicator to measure the product of H.X. oxidation to monitor fish freshness.

Smart packaging using pH-sensitive dyes and antimicrobial agents have also been developed to monitor food quality and safety. Kim et al. [[42](#fortytwo)] observed color changes in the polymer depending on the changes in pH and TVB-N values during the storage of shrimps packed with pea flower anthocyanin as a pH indicator and gelatin/agar polymer integrated with ZnO as an antimicrobial agent. İbrahim et al., [[43](#fortythree)] developed a pH sensor with nanocapsulation technique to monitor the freshness of raw fish (Nile perch) and incorporated this sensor into the polymer composite matrix. Qin et al. [[44](#fortyfour)] incorporated silver nanoparticles and purple corn extract into the chitosan matrix to develop active-smart hybrid food packaging films, which can be used to monitor the freshness of packaged foods. Aghaei et al. [[45](#fortyfive)] used cellulose acetate nanofibers as bio-based polymer packaging as fish spoilage indicator and applied alizarin halochromic sensor to the packaging to provide information about the quality of the product visually.

**5.0. Potential Health Risks, Safety Concerns, Toxicity Issues and Other Associated Challenges**

The production of safe and cost-effective edible delivery systems remains a challenging task [[46](#fortysix)]. However, the use of nanopackages in food packaging poses a significant health risk due to the potential migration or leaching of nanomaterials into the food, depending on the nature of the packaging matrix, toxicity of the nanomaterial, and the degree of migration and uptake rate of the food [[47](#fortyseven)]. Exposure to high amounts of these particles, either through inhalation or skin absorption, can lead to long-term toxicity and accumulation in organs such as the stomach, small intestine, kidneys, liver, and spleen [[48](#fortyeight)]. This can result in kidney and lung damage, hepatic injury, and other health issues [[49](#fortynine),[50](#fifty)].

The uncertainty surrounding the environmental fate of nanoparticles is widely recognized [[51](#fiftyone)]. However, the increasing use of nanoparticles in the food industry, including aquatic foods, fruits, vegetables, and poultry, as well as their production, has the potential to introduce nanomaterials into the environment, increasing the likelihood of their migration. Sadeghi et al. [[52](#fiftytwo)] reported that nanoparticles could contaminate groundwater aquifers, rendering them non-potable. Additionally, nanoparticles could have an impact on atmospheric radiation, visibility, and climate change [[53](#fiftythree)]. The presence of other particles in the atmosphere could interact with nanoparticles, leading to changes in radiative forcing, which could result in warming or cooling effects and changes in ozone levels [[53](#fiftythree)].

Further research is needed to fully understand the potential harmfulness and functionalities of nanomaterials and to ensure their safe application in practical settings [[54](#fiftytfour)]. Chemical methods of nanoparticle synthesis often have negative environmental impacts, resulting in severe pollution [[55](#fiftytfive)]. Regulatory policies, public awareness, risk assessment programs, and biosafety concerns should also be taken into consideration during the processing and consumption of nanotechnology-based food products and their packaging [[56](#fiftysix),[57](#fiftyseven)].

**6.0. Conclusion**

The food industry has seen significant progress in nanotechnology, particularly in the area of food packaging. Nanoparticles are incorporated into polymers and biopolymers to improve the structural properties of food packages, such as gas barrier permeability, flexibility, and durability. They are also used in active packages to preserve the freshness of perishable foods and extend the shelf life of products. Smart packages are also being developed to ensure product traceability, and the use of hybrid packaging systems with nanoparticle-supported nanoparticles and combinations of active-smart packaging have been explored in numerous studies. While the incorporation of nanoparticles in food packaging promotes food safety, it also raises concerns about consumer knowledge, trust, legal regulations, and environmental and human health effects. To address these concerns, more scientific studies are needed.

**7.0. References**

1. MPEDA. Annual Report. “Marine Products Export Development Authority”, Kochi, pp. 384.
2. FAO. Annual Report. “The State of World Fisheries and Aquaculture”, Rome, Italy, 2021, pp. 266.
3. S.S. Salim, “Fish consumption pattern in India, exports‐Overview”, Food Beverages. Vol. *8*, pp. 25–28, August 2016.
4. N. Rahmaniya, M. Sekharan, “Consumer behaviour towards seafood and seafood safety”, Int. J. Curr. Adv. Res., 1st ed., vol. 7, pp. 8727-8736, January 2018.
5. E. Prato, and F. Biandolino. “The Contribution of Fish to the Mediterranean diet”, In the Mediterranean Diet, Academic Press, 2015, pp. 165-174.
6. N. Bhaskar, K. Miyashita, and M. Hosakawa, “Physiological effects of Eicosapentaenoic Acid (EPA) and Docosahexaenoic Acid (DHA) - A Review”. Food Rev. Int., vol. 22, pp. 291-307, September 2006.
7. L. Gram, and H.H. Huss, “Microbiological spoilage of fish and fish products”, Int. J. Food Microbiol., vol. 33, pp. 121–137, November 1996.
8. R. Dobrucka, “The future of active and intelligent packaging industry”, Sci. J. Logist. 2nd ed., vol. 9, pp. 103-110, April 2013.
9. L. Kuuliala, Y. Al Hage, A.G. Ioannidis, M. Sader, F.M. Kerckhof, M. Vanderroost, N. Boon, B. De Baets, B. De Meulenaer, P. Ragaert, and F. Devlieghere, “Microbiological, chemical and sensory spoilage analysis of raw Atlantic cod (*Gadus morhua*) stored under modified atmospheres”, Food Microbiol., vol. 70, pp. 232-244, April 2018.
10. Y. Ge, Y. Li, Y. Bai, C. Yuan, C. Wu, and Y. Hu, “Intelligent gelatin/ oxidized chitin nanocrystals nanocomposite films containing black rice bran anthocyanins for fish freshness monitoring”, Int. J. Biol. Macromol., vol. 155, pp. 1296-1306, July 2020.
11. Z. Dong, F. Xu, I. Ahmed, Z. Li, H. and Lin, “Characterization and preservation performance of active polyethylene films containing rosemary and cinnamon essential oils for Pacific white shrimp packaging”, Food Control, vol. 92, pp. 37-46, October 2018.
12. F. Licciardello, S. Kharchoufi, G. Muratore, C. Restuccia, “Effect of edible coating combined with pomegranate peel extract on the quality maintenance of white shrimps (*Parapenaeus longirostris*) during refrigerated storage”, Food Packag. Shelf Life., vol. 17, pp. 114-119, September 2018.
13. Y. Küçükçobanoğlu, and L. Yıldız Aktaş, “Nanokompozit Kaynağı ve Uygulama Alanı Olarak Bitkiler”, Marmara Üniv. fen bilim., vol. 4, pp. 429- 436, December 2018.
14. B. Finnigan. “Barrier polymers”, The Wiley Encyclopedia of Packaging Technology, K.L. Yam, Eds. New York: John Wiley & Sons, 2010.
15. J. Sarfraz, T. Gulin-Sarfraz, J. Nilsen-Nygaard, M.K. Pettersen, "Nanocomposites for food packaging applications: An overview", Nanomaterials, vol. 11, pp. 10-36, December 2020.
16. H. Zou, S. Wu, and J. Shen, “Polymer/silica nanocomposites: preparation, characterization, properties, and applications”, Chem. Rev., vol. 108, pp. 3893-3957, August 2008.
17. K. Yano, A. Usuki, A. Okada, T. Kurauchi, O. Kamigaito, “Synthesis and properties of polyimide-clay hybrid”, J. Polym. Sci., Part A: Polym. Chem., vol. 31, pp. 2493-2498, September 1993.
18. B.N. Jung, D. Kang, S. Cheon, J.K. Shim, and S.W. Hwang, “The addition effect of hollow glass microsphere on the dispersion behavior and physical properties of polypropylene/clay nanocomposites”, J. Appl. Polym. Sci., vol. 136, pp. 47476-47487, December 2018.
19. G. Wang, G. Zhao, G. Dong, Y. Mu, and C.B. Park, “Lightweight and strong microcellular injection molded PP/talc nanocomposite”, Compos. Sci. Technol., vol. 168, pp. 38–46, November 2018.
20. Y. Huang, J. Limqueco, X.Y. Chieng, X. Li, and W. Zhou, “Performance evaluation of a novel food packaging material based on clay/polyvinyl alcohol nanocomposite”, Innov Food Sci Emerg Technol, vol. 43, pp. 216-222, October 2017.
21. A. Khanipour. Z.A. Bahmani, A.R. Oromiehie, A.A. Motalebi, “Effect of packaging with nano-composite clay/LDPE film on the quality of rainbow trout (*Oncorhynchus mykiss*) fillet at refrigerated storage”, Iran. J. Fish. Sci., vol. 19, pp. 698–714, March 2020.
22. M. Alboofetileh, M. Rezaei, H. Hosseini, and M. Abdollahi, “Morphological, physico‐mechanical, and antimicrobial properties of sodium alginate‐montmorillonite nanocomposite films incorporated with marjoram essential oil”, J. Food Process. Preserv., 5th ed., vol. 42, pp. 13596-13604, February 2018.
23. J.F. Rubilar, D. Candia, A. Cobos, O. Diaz, F. Pedreschi, “Effect of nanoclay and ethyl-Nα-dodecanoyl-l-arginate hydrochloride (LAE) on physico-mechanical properties of chitosan films”, LWT, vol. 72, pp. 206-214, October 2016.
24. B.S. Chiou, R.J. Avena-Bustillos, P.J. Bechtel, S.H. Imam, G.M. Glenn, and W.J. Orts, “Effects of drying temperature on barrier and mechanical properties of cold-water fish gelatin films”, J Food Eng., 2nd ed., vol. 95, pp. 327-331, November 2009.
25. A. Farahnaky, S.M. Dadfar, and M. Shahbazi, “Physical and mechanical properties of gelatin-clay nanocomposite”, J. Food Eng., vol. 122, pp. 78–83, February 2014.
26. H. Staroszczyk, E. Malinowska-Panczyk, K. Gottfried, and I. Kołodziejska, “Fish gelatin-nanoclay films. Part I: effect of a kind of nanoclays and glycerol concentration on mechanical and water barrier properties of nanocomposites”, J. Food Process. Preserv., vol. 41, pp. 13211-13217, February 2017.
27. F. Vilarinho, M.A. Andrade, G. Buonocore, M. Stanzione, M. Vaz, and A.S. Silva, “Monitoring lipid oxidation in a processed meat product packaged with nanocomposite poly (lactic acid) film”, Eur. Polym. J., vol. 98, pp. 362–367, January 2018.
28. A.S. Eddin, and R. Tahergorabi, “Application of a surimi-based coating to improve the quality attributes of shrimp during refrigerated storage”, Foods, 9th ed., vol. 6, 76-87, September 2017.
29. D. Enescu, M.A. Cerqueira, P. Fucinos and L.M. Pastrana, “Recent advances and challenges on applications of nanotechnology in food packaging: A literature review”, Food Chem. Toxicol., vol. 134, pp. 110814-110819, January 2019.
30. S. Singh, M. Lee, K.K. Gaikwad, and Y.S. Lee, “Antibacterial and amine scavenging properties of silver-silica composite for post-harvest storage of fresh fish”, FBP, vol. 107, pp. 61–69, November 2017.
31. H. Efatian, H. Ahari, D. Shahbazzadeh, B. Nowruzi, and S. Yousefi, “Fabrication and characterization of LDPE/silver-copper/titanium dioxide nanocomposite films for application in nile tilapia (*Oreochromis niloticus*) packaging”, J. Food Meas. Charact., 3rd ed., vol. 15, pp. 2430- 2439, February 2021.
32. S. Paidari, and H. Ahari, “The effects of nanosilver and nanoclay nanocomposites on shrimp (*Penaeus semisulcatus*) samples inoculated to food pathogens”, Food Measure, vol. 15, pp. 3195–3206, March 2021.
33. H. Esmailzadeh, P. Sangpour, F. Shahraz, A. Eskandari, J. Hvizinii, and R. Khaksar, “CuO/LDPE nanocomposite for active food packaging application: A comparative study of its antibacterial activities with ZnO/ LDPE nanocomposite”, Polym. Bull., vol. 78, pp. 1671-1682, October 2020.
34. M. Alizadeh-Sani, M. Tavassoli, E. Mohammadian, A. Ehsani, G.J. Khaniki, R. Priyadarshi, and J.W. Rhim, “pH-responsive color indicator films based on methylcellulose/chitosan nanofiber and barberry anthocyanins for real-time monitoring of meat freshness”, Int. J. Biol. Macromol., vol. 166, pp. 741-750, January 2021.
35. K.B. Biji, C.N. Ravishankar, C.O. Mohan, and T.K. Srinivasa Gopal, “Smart packaging systems for food applications: A review”, J. Food Sci. Technol., 10th ed., vol. 52, pp. 6125-6135, October 2015.
36. A.G. Ponce, J.F. Ayala-Zavala, N.E. Marcovich, F.J. Vázquez, M.R. Ansorena, “Nanotechnology trends in the food industry: Recent developments, risks, and regulation”, Impact of Nanosci. in the Food Industry, pp. 113-141, January 2018.
37. C. Wu, J. Sun, P. Zheng, X. Kang, M. Chen, Y. Li, Y. Ge, Y. Hu, and J. Pang, “Preparation of an intelligent film based on chitosan/oxidized chitin nanocrystals incorporating black rice bran anthocyanins for seafood spoilage monitoring”, Carbohydr. Polym., vol. 222, 115006-115014, October 2019.
38. S. Naghdi, R. Masoud, and A. Mehdi, “A starch-based PH-sensing and ammonia detector film containing betacyanin of paperflower for application in intelligent packaging of fish”, Int. J. Biol. Macromol., vol. 191, pp. 161–170, November 2021.
39. A. Lapenna, M. Dell’Aglio, G. Palazzo, A. Mallardi, “Naked gold nanoparticles as colorimetric reporters for biogenic amine detection”, Colloids Surf. A: Physicochem. Eng., vol. 600, pp. 124903-124912, September 2020.
40. X. Zhai, Z. Li, J. Shi, X. Huang, Z. Sun, D. Zhang, X. Zou, Y. Sun, J. Zhang, M. Holmes, Y. Gong, M. Povey, S. Wang, “A colorimetric hydrogen sulfide sensor based on gellan gum-silver nanoparticles bionanocomposite for monitoring of meat spoilage in intelligent packaging”, Food Chem., vol. 290, pp. 135-143, August 2019.
41. F. Mustafa, A. Othman, and S. Andreescu, “Cerium oxide-based hypoxanthine biosensor for fish spoilage monitoring”, Sens. Actuators B: Chem., vol. 332, pp. 129435-129442, April 2021.
42. H.J. Kim, S. Roy, J.W. Rhim, “Gelatin/agar-based color-indicator film integrated with *Clitoria ternatea* flower anthocyanin and zinc oxide nanoparticles for monitoring freshness of shrimp”, Food Hydrocoll., vol. 124, 107294-107306, March 2022.
43. S. Ibrahim, F. Hager, and S. Shimaa, “Application of interactive and intelligent packaging for fresh fish shelf-Life monitoring”, Front. nutr., vol. 8, pp. 677884-677891, June 2021.
44. Y. Qin, Y. Liu, L. Yuan, H. Yong, and J. Liu, “Preparation and characterization of antioxidant, antimicrobial and pH-sensitive films based on chitosan, silver nanoparticles and purple corn extract”, Food Hydrocoll., vol. 96, pp. 102-111, November 2019.
45. Z. Aghaei, B. Emadzadeh, B. Ghorani, and R. Kadkhodaee, “Cellulose acetate nanofibres containing alizarin as a halochromic sensor for the qualitative assessment of rainbow trout fish spoilage”, Food Bioprocess Technol., vol. 11, pp. 1087-1095, May 2018.
46. C. Dupas, and M. Lahmani, “Nanoscience: Nanotechnologies and Nanophysics”. Springer Science & Business Media, 2007.
47. M. Cushen, J. Kerry, M. Morris, M. Cruz-Romero, and E. Cummins, “Nanotechnologies in the food industry–recent developments, risks and regulation”, Trends Food Sci., 1st ed., vol. 24, pp. 30-46, March 2012.
48. D.J. McClements, and H. Xiao, ‘Is nano safe in foods? Establishing the factors impacting the gastrointestinal fate and toxicity of organic and inorganic food-grade nanoparticles”, Npj Sci. Food, 1st ed., vol. 1, pp. 6-18, November 2017.
49. M. Esmaeillou, M. Moharamnejad, R. Hsankhani, A.A. Tehrani, and H. Maadi, “Toxicity of ZnO nanoparticles in healthy adult mice”, Environ. Toxicol. Pharmacol., 1st ed., vol. 35, pp. 67-71, January 2013.
50. Y. Yang, K. Doudrick, X. Bi, K. Hristovski, P. Herckes, P. Westerhoff, and R. Kaegi, “Characterization of food-grade titanium dioxide: the presence of nanosized particles”, Environ. Sci. Technol., 11th ed., vol. 48, pp. 6391-6400, April 2014.
51. E. Kabir, V. Kumar, K.H. Kim, A.C. Yip, J.R. Sohn, “Environmental impacts of nanomaterials”, J. Environ. Manage.”, vol. 225, pp. 261-271, November 2018.
52. R. Sadeghi, R.J. Rodriguez, Y. Yao, and J.L. Kokini, “Advances in nanotechnology as they pertain to food and agriculture: benefits and risks”, Annu. rev. food sci. technol., vol. 8, pp. 467-492, January 2017.
53. J. Bottero, M. Auffan, D. Borschnek, P. Chaurand, J. Labille, C, Levard, A. Masion, M. Tella, J. Rose, and M.R. Wiesner, “Nanotechnology, global development in the frame of environmental risk forecasting. A necessity of interdisciplinary researches”, C. R. - Geosci., 1st ed., vol. 347, pp. 35–42, January 2015.
54. S. Das, L. Jagan, R. Isiah, B. Rajesh, S. Backianathan, and J. Subhashini, J, “Nanotechnology in oncology: Characterization and in vitro release kinetics of cisplatin-loaded albumin nanoparticles: Implications in anticancer drug delivery”. Indian J. Pharmacol., 4th ed., vol. 43, 409-413, July 2011.
55. G. Singhal, R. Bhavesh, K. Kasariya, A.R. Sharma, and R.P. Singh, “Biosynthesis of silver nanoparticles using *Ocimum sanctum* (Tulsi) leaf extract and screening its antimicrobial activity”, J Nanopart Res, vol. 13, pp. 2981-2988, January 2011.
56. V.K. Bajpai, M. Kamle, S. Shukla, D.K. Mahato, P. Chandra, S. Hwang, P. Kumar, J.S. Yu, and Y.S. Huh, “Prospects of using nanotechnology for food preservation, safety, and security”. J Food Drug Anal., 4th ed., vol. 26, pp. 1201–1214, October 2018.
57. Y. Yu, S. Zhang, Y. Ren, H. Li, X. Zhang, and J. Di, “Jujube preservation using chitosan film with nano-silicon dioxide”, J. Food Eng., 13th ed., vol. 113, pp. 408-414, December 2012.