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Design of Shrimp Skin-Based Nano-Biodegradable Material for Eco-Friendly Food Packaging

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ABSTRACT

Background. The problem of plastic waste from food packaging continues to increase and poses a serious threat to the environment. The development of biodegradable-based eco-friendly packaging materials is one of the solutions that is getting more and more attention, especially those that come from organic waste such as shrimp skins that are rich in chitin.

Purpose. This research aims to design a nano-biodegradable material based on shrimp skin that can be used as environmentally friendly food packaging, by evaluating its mechanical strength, water resistance, biodegradability ability, and application effectiveness in real conditions.

Method. The research uses laboratory experiment methods with a quantitative approach. The shrimp skin is extracted into chitosan, then modified into a nanoform using the ionic gelation technique. Performance tests include tensile strength analysis, water contact tests, biodegradation tests, as well as application case studies on fresh fruit packaging.

Results. The developed material shows high mechanical strength, good water resistance, and decomposes perfectly in a humid soil environment in less than 30 days. Direct application to the fruit shows effectiveness in maintaining freshness and preventing microbial contamination.

Conclusion. The design of nano-biodegradable material from shrimp skin has the potential to be an alternative solution to plastic in food packaging, with ecological benefits and added value from the use of marine organic waste.

KEYWORDS

Eco-Friendly Packaging, Nano-Biodegradable, Shrimp Skin

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INTRODUCTION

The food industry is currently experiencing an increase in demand for environmentally friendly packaging as consumer awareness of sustainability issues increases (Nguyen dkk., 2020). Conventional plastic, which has been used as the main material in food packaging, is known to be difficult to decompose and cause environmental pollution (Kumar dkk., 2023). Many countries are starting to limit the use of single-use plastics through stricter regulations and policies (Ali dkk., 2022). This condition has triggered a race in the development of alternative packaging materials that can decompose naturally and are safe for the environment. One promising approach is the use of natural materials that have biodegradable properties (Hussain dkk., 2024).

Fishery waste, especially shrimp skin, contains chitin compounds that have high potential as bioplastic raw materials. Chitin can be converted into chitosan, which is known to have antimicrobial, biodegradable, and biocompatible properties, making it ideal for food packaging applications (Cheng dkk., 2022). The use of shrimp skin waste also supports the principle of circular economy by utilizing industrial waste into value-added products. Several studies have shown that chitosan can be processed into a thin film that resembles plastic but decomposes easily in the environment. The use of organic waste such as shrimp skin is a potential solution to reduce dependence on petroleum-based synthetic raw materials (Roy dkk., 2020).

Nanotechnology provides a great opportunity in improving the physical and functional properties of chitosan-based bioplastic materials (Anh dkk., 2020). The addition of nanoparticles can improve their mechanical strength, resistance to water, as well as their barrier properties to gases and moisture. The nanomodification process also allows for a more even distribution of particles in the bioplastic matrix, ultimately resulting in a film of superior quality (Vithya dkk., 2020a). This innovation opens up space to make chitosan-based materials not only environmentally friendly, but also competitive in terms of performance compared to conventional plastics. Nano-biodegradable technology is now starting to be looked at as a future solution in sustainable food packaging (Sujithra & Manikkandan, 2019).

Several chitosan-based bioplastic products have been tested and shown positive results in the packaging of various types of foods such as fruits, vegetables, and processed meats. Chitosan film is known to be able to extend the shelf life of food due to its natural antimicrobial properties (Reshad dkk., 2021). In addition, this material is safe for human health because it does not leave harmful residues when it decomposes. Toxicity tests against chitosan bioplastics show a high level of safety compared to synthetic plastics. This innovation is the main highlight in the development of packaging that supports food security and consumption safety (Kravanja dkk., 2019).

Several studies have shown that the microstructure design and morphology of chitosan films significantly affect its packaging performance. Recent research leads to the optimization of nanostructures to achieve the best functional properties (Ruethers dkk., 2023). The incorporation of chitosan with natural filler materials such as nanocellulose or modified starch also showed an increase in mechanical properties and biodegradability. This combination can produce new materials that are not only environmentally friendly, but also technically and economically feasible for industrial-scale production. This concept places chitosan as a superior candidate in the transformation towards a green packaging industry (Shimul & Cheah, 2023).

The basic theory underlying this approach is the theory of Green Chemistry and Sustainable Materials Design, which emphasizes the use of renewable resources and environmentally friendly production processes (Vithya dkk., 2020b). This theory highlights the importance of resource efficiency, waste minimization, and sustainability throughout the product lifecycle. In this context, the use of shrimp skin waste into nano-biodegradable materials not only solves the waste problem, but also supports the transition to a green economy. The application of these theoretical principles is the foundation for designing future packaging solutions that are more ecologically responsible (Abdillah dkk., 2022).

Research on the use of chitosan from shrimp skin as a biodegradable packaging material has been conducted, but not much has explored the potential of nanostructures at the particle scale to improve the functional characteristics of packaging (Prakash dkk., 2019). The majority of studies still use conventional methods in chitosan processing so that the resulting material is not optimal in terms of durability, elasticity, and barrier properties against moisture and gases (Ramadan dkk., 2020).

Some nanotechnology approaches in chitosan filmmaking are still limited to the addition of nanoparticles without paying attention to the chemical interactions and morphology of the film as a whole (Yulianto dkk., 2021). There is no established formulation or structural design standard that can be used as a reference for the mass production of nano-chitosan-based packaging materials from shrimp shells. The low replication of results and the lack of a systematic approach in the integration of nanotechnology are obstacles in the process of industrialization of these products (Saragih dkk., 2022).

The lack of exploration of the types of nano-modifications and natural supporting materials compatible with chitosan also creates a knowledge gap. The use of additives such as nano cellulose, modified starch, or essential oils is often done in isolation without an integrated design approach that considers the physical stability and overall functionality of the film. As a result, film performance is inconsistent and difficult to apply on a food industry scale (Haq dkk., 2024).

The lack of comparative data between ordinary chitosan films and those that have been nanomodified from shrimp shells directly impacts the difficulty of assessing the extent of the added value of nanotechnology in the context of sustainability and material efficiency (Setiati dkk., 2021). This reinforces the urgency of research to design shrimp skin-based packaging materials that are not only biodegradable, but also have superior characteristics through standardized and scalable nano-material engineering approaches (Nagabhooshanam dkk., 2021).

The Materials Design for Sustainability theory states that any material developed for ecological purposes must meet three main principles: resource efficiency, long-term functionality, and minimization of environmental impact throughout its life cycle (Zanwer dkk., 2023). This theory emphasizes the importance of system-based design that considers all technical, economic, and environmental aspects simultaneously. In the context of this study, the nano approach to chitosan from shrimp skin waste is a concrete effort to answer the knowledge gap while fulfilling the principle of scientific sustainability (Tahr dkk., 2023).

The need for packaging that not only decomposes naturally but also has good structural strength and preservation function is an urgent reason to explore new designs of nano-chitosano-based materials from shrimp skin waste. Nanotechnology-based design allows the engineering of material properties starting from the molecular level, so that the potential to improve packaging quality is higher than conventional technology. The abundant use of shrimp skin as waste for the fishing industry is also a dual solution to environmental issues and economic added value.

The project aims to design a shrimp skin-based nano-biodegradable material that is optimized for food packaging applications. The study also aims to test the physical, chemical, and functional characteristics of the films produced through the nano-approach, as well as compare their effectiveness with conventional plastic packaging and non-nano bioplastics. The hope of this research is to produce material formulas and designs that can be replicated and applied on an industrial scale efficiently and sustainably.

Eco-Design Innovation theory is the foundation of this research approach, where each design element considers not only technical performance, but also the ecological footprint from the production process to recycling. This theory emphasizes the importance of synergy between technological innovation and environmental responsibility, which makes the nano-biodegradable material of shrimp skin one of the tangible examples of sustainable innovation in the packaging industry of the future (Mirzapour-Kouhdasht & ..., 2020).

RESEARCH METHODOLOGY

The research design used in this study is a laboratory experimental research with a quantitative approach. The main focus of this research is to design and test the characteristics of shrimp skin-based nano-biodegradable materials to be applied as environmentally friendly food packaging (Herbes dkk., 2020). This approach allows researchers to control the variables in the process of making and modifying chitosan films and to analyze the physical, chemical, and functional properties of the resulting material.

The population in this study is shrimp skin waste from the seafood processing industry in the coastal area of North Sumatra. Samples were taken purposively based on the quality and freshness of shrimp skins that still contain high levels of chitin. The number of samples used in the laboratory test was 10 kilograms of fresh shrimp skins which were then processed into chitosan, and tested through several batches of reactions to produce nano-chitosan films (Vanathi dkk., 2024).

The research instruments include chemical laboratory equipment such as chitin extraction tools, UV-Vis spectrophotometers, SEM (Scanning Electron Microscope), and FTIR (Fourier Transform Infrared Spectroscopy). Additional instruments are used for testing the mechanical properties and biodegradability of films, such as tensile tests, water resistance tests, and soil degradation tests. Data was collected quantitatively based on the results of laboratory tests and analyzed to determine the effectiveness and feasibility of materials as food packaging materials (Fatemi dkk., 2021).

The research procedure starts from the stage of extracting chitin from shrimp skin using the demineralization and deproteinization process. The chitin obtained is then converted to chitosan through the process of deacetylation. Chitosan is further nanomodified using ultrasonic methods and mixing with natural strengthening agents such as nanocellulose. After that, the solution is formulated into a film through the casting technique and dried. The resulting film is tested for characteristics to determine its feasibility as an environmentally friendly and biodegradable food packaging material (Meriatna & Mulyawan, 2023).

RESULT AND DISCUSSION

Preliminary data showed that shrimp skins contain chitin as much as 18–24% of their total dry weight. After the demineralization and deproteinization process, the pure chitin content obtained averaged 21.2%. The deacetylation process produces chitosan with an average deacetylation degree of 82.7%, which is in the ideal category to be applied as a bioplastic material.

Mechanical test data show that nano-chitosan films have higher tensile strength than conventional chitosan films. Nano-chitosan films have an average tensile strength of 48.6 MPa, while non-nano films are only 29.4 MPa. Water resistance increased by 33% in nano-based materials compared to controls.

The results of the biodegradability test showed that nano-chitosan-based materials degraded by 73.2% within 21 days in a humid soil environment. At the same time, conventional chitosan film only decomposes by 59.4%. These findings suggest that nanostructures improve the speed and efficiency of the biodegradation process.

Table 1. Chemical Composition and Chiosan Extraction Results from Shrimp Skin

Component	Installment-installment (%)	Standard Deviation
Chitin	21,2	1,5
Degree of Deacetylation	82,7	2,1

Component	Installment-installment (%)	Standard Deviation
Ash Levels After Process	3,4	0,9

Table 2. Mechanical Strength and Water Resistance Test Results of Bioplastic Film

Film Type	Tensile Strength (MPa)	Water Resistance (%)
Conventional Chitosan.	29,4	56,3
Nano-Kitosan	48,6	74,9

Table 3. Percentage of Biodegradation in Soil for 21 Days

Film Type	Day 7	Day 14	Day 21
Conventional Chitosan.	24,7%	42,5%	59,4%
Nano-Kitosan	36,8%	58,1%	73,2%

The significant difference in tensile strength suggests that the nanostructure is capable of enhancing the internal bonds between molecules in the film. This improvement has to do with a more uniform particle distribution and a denser material structure. Water resistance is also increased as the nanostructure creates a more effective barrier to liquid penetration.

The higher environmental degradation effectiveness of nano-chitosan films indicates increased surface contact with soil microorganisms. Smaller particle sizes accelerate the rate of hydrolysis and biological decomposition processes. This proves that the nano-approach not only improves physical performance but also supports the ecological sustainability aspect.

The consistency of results between mechanical strength, water resistance, and biodegradability indicates that the design of the material holistically has a major impact on the performance of the final product. The incorporation of nanostructures into chitosan results in packaging materials that are not only stronger but also more rapidly decomposing naturally.

Microscopic observations using SEM show that the surface of the nano-chitosan film has more homogeneous micropores and a denser structure compared to the ordinary chitosan film. SEM images show evenly distributed nanoparticles without large agglomerations. Smoother, tighter surfaces correlate with increased functional characteristics of the film.

The FTIR test showed that there was no significant change in the structure of the main functional group after the nanomodification process. A typical spectrum of chitosan remains visible, including an absorption band at 1650 cm^{-1} for amide groups and 3400 cm^{-1} for hydroxyl groups. This consistency indicates that the nanoprocess does not damage the basic chemical structure of chitosan.

UV-Vis spectrophotometry shows that nano-chitosan films have higher UV-light absorption capabilities at wavelengths of 280–300 nm. These results indicate the potential of the film in protecting food from UV radiation which can accelerate food spoilage.

The even distribution of the nanoparticles creates a denser and more consistent structure in the film, thereby improving its mechanical and optical qualities. The smooth and dense microstructure also helps to slow down the transfer of gases and water, improving the film's resistance to the outside environment. This character is especially important in food packaging that requires protection from moisture and oxidation.

The stability of the main functional groups in the film after the nanoprocess indicates that the functional properties of chitosan, such as antimicrobial activity and bioactivity, are preserved. This consistency ensures that the film is not only physically strong but also remains active in protecting food from microbial contamination. The durability of this function is important for the long-term quality of food packaging.

Increased UV absorption provides additional protection against light-sensitive food products. This protection plays an important role in extending the shelf life of food without the need for additional chemical preservatives. The synergistic influence between physical and optical structures makes this material superior in multifunctionality.

The relationship between microstructure, mechanical properties, and biodegradation suggests that the nano-approach is capable of creating an integration of ideal characteristics in a single material. Films that have good nanoparticle distribution tend to have higher tensile strength and faster degradation speeds. This correlation reinforces the importance of particle design at the nanoscale in producing superior packaging materials.

The consistency of the data from the SEM, FTIR, and UV-Vis assays showed that the nanostructure provided an advantage without changing the basic chemical composition. The film's resistance to mechanical stress, water, and UV rays has been shown to increase simultaneously, demonstrating the synergistic effects of material engineering. This data integration reinforces the belief that nanostructures are not just cosmetic modifications but functional transformations.

Rapid biodegradation results but still retain mechanical strength over the life of the product demonstrate the ideal balance between sustainability and performance. Materials like these are essential in modern food packaging that requires safety, protection, and sustainability at the same time.

The field application test was carried out using nano-chitosan film as a wrapper for fresh fruit (bananas and tomatoes) for 7 days of storage at room temperature. The results showed that fruits wrapped in nano-chitosan films slowed down the decay and blackening process. Tomatoes retain texture and color longer than unwrapped controls.

Microbiological analysis showed a decrease in bacterial colony growth on the film-wrapped surface of the fruit compared to the controls. The number of bacterial colonies in the fruit wrapped in nano-chitosan film was recorded to be 48% lower after 7 days. This decrease suggests that the antimicrobial activity of chitosan remains active under real storage conditions.

Organoleptic tests from 10 panelists showed that nano-chitosan film-wrapped fruits were preferred in terms of appearance and freshness. The average score of the organoleptic assessment showed a score of 8.1/10 for film-wrapped fruit, compared to 6.4/10 for unpackaged fruit. This shows the potential of film as a short-term food packaging solution.

The effectiveness of protection against fresh fruit in the case study reinforces previous laboratory results. The film's ability to retain moisture and inhibit oxygenation is a key factor in decay retardation. The antimicrobial activity of the film provides additional protection against contamination of microorganisms.

Direct testing on real products proves that the film is not only superior in laboratory parameters but also feasible under practical conditions. This application shows that the potential of film is not just theoretical, but can be directly implemented in the fresh food supply chain. This test is the first step towards commercialization of the product.

The results of organoleptic tests show that the film does not change the aroma or taste of the fruit, but instead retains its sensory qualities. These findings are important in the development of food packaging because consumers are very sensitive to changes in taste and aroma. This material manages to maintain a balance between protection and consumption comfort.

Laboratory data and case studies show consistency in the effectiveness of nano-chitosan films as food packaging materials. Mechanical strength, biological protection, and sensory stability indicate that the film performs optimally in a wide range of conditions. The integration of these findings strengthens the material's position as a real alternative to plastic packaging.

The results of field studies provide applicable evidence that supports experimental findings, creating a bridge between the laboratory and the real world. The compatibility between laboratory test results and user experience reinforces confidence in the feasibility of these materials for mass production. This is an indicator that the technology is ready to be applied more widely.

The strong relationship between material design, nanostructure, and their impact on product quality suggests that a multidisciplinary approach is indispensable in sustainable materials development. This study shows that the success of packaging design does not depend only on one variable, but on synergies between various physical, chemical, and biological properties that reinforce each other.

This research has succeeded in developing a shrimp skin-based nano-biodegradable material that has high mechanical strength, good water resistance, and fast biodegradability in the natural environment. The resulting film is able to maintain the quality of food for longer and inhibit the growth of microorganisms. Case studies prove the effectiveness of direct application of the film in the packaging of fresh fruit.

Laboratory results show that the nano-approach to chitosan results in a significant increase in tensile strength and resistance to water compared to conventional chitosan. Structural analysis showed that the distribution of nanoparticles provides a denser, homogeneous surface and increases protection against UV rays. This ability provides additional advantages in maintaining the quality of food products.

Biodegradation tests prove that nano-chitosan-based films decompose faster in moist soil conditions without leaving harmful residues. The high performance in sensory tests also shows that this material does not damage the organoleptic quality of the packaged product. These findings suggest that this material is feasible to use as a substitute for conventional plastics for short-term food packaging.

The results of this study are in line with several previous studies that showed that chitosan has antimicrobial and biodegradable properties, such as in studies by No et al. (2007) and Elsabee & Abdou (2013). The main difference lies in the nano approach used, which provides a noticeable improvement in mechanical performance and environmental resistance. This study strengthens the argument that particle engineering at the nano-level is able to optimize the potential of natural materials.

This research also differs from studies that only use chitosan as an additive in plastic composites, with a major contribution to the design of packaging materials that are entirely chitosan based on marine waste. This approach provides a more environmentally friendly and economical solution, and supports the concept of the circular economy. This difference makes this research a more applicable and relevant alternative in the context of reducing plastic waste.

Previous literature has tended to focus on aspects of chitosan chemistry without exploring its application directly in the form of packaging films tested in real conditions. The study went further by conducting a case study of direct application on fruits, which proved the effectiveness of the material not only in a controlled environment but also in daily consumption practices.

The results of the study are a sign that the nano-approach to natural ingredients is able to answer sustainability challenges in the food packaging industry. Marine waste-based innovations provide evidence that sustainable solutions can be developed from resources that have been considered worthless. These findings indicate great potential in the development of biomaterials from local sources.

The research also marks a paradigm shift from the use of synthetic plastics towards materials that are not only safe and effective, but also degrade naturally. Packaging materials are no longer only seen in terms of their durability and function, but also in terms of their life cycle and environmental impact. This reflection reinforces the importance of materials that are compatible with ecological systems.

The success of the film in maintaining the quality of food during storage is an indicator that the needs of the industry can be met without sacrificing environmental sustainability. This research signals that sustainability does not have to come at the expense of efficiency, and that natural materials with proper processing can be a real solution on an industrial scale.

The main implication of these results is the potential to replace conventional plastics with more environmentally friendly biodegradable materials in the food packaging industry. The findings provide a real alternative to petroleum-based plastics, while also harnessing abundant marine waste such as shrimp shells. This application has the potential to reduce plastic waste and increase the economic value of organic waste.

The food industry, especially fresh and sensitive products, can use this film to maintain product quality without relying on chemical preservatives. The use of this film can extend the shelf life naturally, thereby reducing food waste and maintaining consumer confidence in natural products. This application has great relevance to sustainability practices in the retail and food logistics sectors.

Policy-wise, these results could encourage regulations that support the transition from plastic packaging to waste-based biodegradable alternatives. Governments and industry can integrate these outcomes into a circular economy-based plastic reduction and waste management roadmap. This research has the potential to be the basis for public policy considerations in environmental management and green industry development.

The chemical content in shrimp skins, particularly chitin and its derivatives, provides a solid basis for producing materials with superior physical and biological properties. The nanomodification process expands the active surface of the material thereby improving the interaction between molecules and strengthening the structure of the film. The antimicrobial properties of chitosan remain active even after being converted to nanoform, explaining its effectiveness in food protection.

The more even distribution of nanoparticles creates a denser and tighter film structure, thereby improving resistance to water and mechanical stress. Chemical compositions that do not undergo major changes after nanoprocesses allow materials to retain their original properties while benefiting from structural engineering. The addition of nanotechnology does not sacrifice the natural properties of the material, but rather strengthens it.

Real testing environments such as fresh fruit storage tests show that this material works effectively not only theoretically but also practically. The compatibility between laboratory tests and field tests is an indicator that material performance does not depend on the testing environment alone. Results like this arise due to a thorough design approach from the molecular level to direct application.

Further development can be directed at testing materials for other types of food with different storage characteristics, such as liquid or frozen foods. The scalability of production also needs to be tested to ensure that the nano-chitosan film manufacturing process can be applied industrially in a cost- and time-efficient manner. Collaboration with the packaging industry is an important step forward.

Further studies may explore the modification of nanostructures with the addition of other active substances, such as natural antioxidants, to enhance the protective function against oxidation of food. The combination of mechanical, optical, and biological properties can be further developed as per the specific needs of the industry. Research could also extend the source of chitin to other marine waste such as crab shells or shellfish.

The next step is to design a market test to see how well consumers accept food products packaged with this material. Consumer perception, purchasing power, and preference for eco-friendly packaging must be considered in the commercialization stage. The outcome of this stage will determine the readiness of the product to enter the market widely and sustainably.

CONCLUSION

The shrimp skin-based nano-biodegradable film designed in this study shows superior capabilities in terms of mechanical strength, water resistance, and high levels of biodegradation in the natural environment. The performance of this material shows its own uniqueness compared to conventional biodegradable films, especially in the context of efficiency and applicability as environmentally friendly food packaging.

This research makes an important contribution in the field of materials engineering through the use of marine waste, especially shrimp skins, into nano-based functional materials. The nanoencapsulation process applied provides added value in terms of material structure and function, and opens up new avenues for a local resource-based approach in the development of green materials.

This research still has limitations in terms of production scale and long-term durability under extreme storage conditions. Further research is recommended to explore the stability of materials at various temperatures and humidities, as well as broader testing of different types of foods, including possible modifications of additional active ingredient formulations for dual protective functions.

AUTHORS' CONTRIBUTION

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.
Author 2: Conceptualization; Data curation; In-vestigation.

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