Industrial Shrimp Shell Waste Valorisation Through Chitosan-Based Bioplastic Film Development

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Abstract

The rapid growth of the shrimp aquaculture industry has led to the generation of substantial quantities of shrimp shell waste, much of which is disposed of through environmentally unsustainable practices despite its high content of valuable biopolymers such as chitin and chitosan. Although previous studies have demonstrated the potential of shrimp-shell-derived chitosan for bioplastic production, most have relied on laboratory-scale materials obtained from non-traceable sources, thereby limiting their practical relevance to industrial waste valorisation. To address this gap, the present study utilised shrimp shell waste sourced directly from a traceable commercial shrimp farm to establish a traceable link between industrial aquaculture waste and the development of sustainable materials. In this study, chitosan was extracted from shrimp shell waste through sequential demineralisation, deproteinisation, and alkaline treatment before being processed into bioplastic films using the solution-casting technique. Three formulations containing 0%, 2%, and 4% (w/v) chitosan were prepared and evaluated in terms of moisture content, tensile strength, elongation at break, and Young's modulus. The extracted chitosan produced homogeneous film-forming solutions and yielded transparent, flexible, and visually uniform films with smooth surface morphology. Mechanical characterisation revealed tensile strength values ranging from 1.11 ± 0.03 to 2.42 ± 0.08 MPa, elongation at break from 31.1 ± 1.5% to 104.3 ± 3.2%, Young's modulus from 1.83 ± 0.2 to 35.8 ± 1.2 MPa, and moisture content between 16.02 ± 1.46% and 25.15 ± 24.76%. Notably, the 2% chitosan formulation exhibited the highest tensile strength, whereas the 4% formulation demonstrated the greatest flexibility. These highlight the characteristic trade-off between stiffness and extensibility commonly observed in biodegradable polymer systems. Overall, the findings demonstrate the feasibility of converting industrial shrimp shell waste into functional bioplastic films and provide practical evidence of a waste-to-material pathway that supports circular economy initiatives within the aquaculture sector. Although further optimisation is required to enhance mechanical performance, the study highlights the potential of industrial shrimp shell waste as a renewable resource for the development of sustainable biodegradable packaging materials.

Keywords: Bioplastic, Chitosan, Shrimp Shell Waste, Sustainable Packaging, Waste Valorisation

1.0 Introduction

The growing emphasis on sustainable resource management and circular economy principles has prompted increasing interest in transforming industrial by-products into value-added materials with both environmental and economic benefits. Within the aquaculture sector, the continued expansion of shrimp farming has substantially increased global shrimp production, consequently generating large quantities of processing residues. Shrimp shell waste, including heads, carapaces, and shells, typically accounts for approximately 30-50% of the total biomass and is often regarded as a low-value by-product within commercial aquaculture operations [1], [2]. However, the accumulation of this waste presents significant environmental challenges. Wan Mahari [3] reported that poor waste management practices in aquaculture contribute considerably to environmental degradation, while Ravi Kumar et al. [4] identified seafood waste as a contributor to greenhouse gas emissions. Common disposal methods, such as landfilling, open burning, and direct discharge into water bodies, accelerate the decomposition of organic matter, leading to odour generation and microbial contamination [5], [6]. Studies investigating the environmental consequences of aquaculture waste have further highlighted its adverse effects on ecosystem stability, water quality, and public health, particularly in coastal regions where aquaculture activities are concentrated [7], [8].

Despite being rich in valuable biopolymers and naturally biodegradable, shrimp shell waste remains underexploited for high-value applications, resulting in both resource inefficiency and unnecessary environmental burdens [1]. Among the most important compounds derived from shrimp shells are chitin and its deacetylated derivative, chitosan, which have attracted considerable attention because of their excellent biocompatibility, biodegradability, and functional versatility. Aranaz et al. [9] identified both materials as promising biomaterials for a wide range of applications, while Chabra et al. [10] demonstrated their potential in film production. More recently, Jin et al. [11] reviewed advances in chitosan-based food packaging systems, including films, coatings, and aerogels, highlighting their film-forming capabilities and antimicrobial properties, as well as the opportunities and challenges associated with their practical application. Similarly, Priyadarshi and Rhim [12] reported that chitosan films possess tuneable physicochemical characteristics suitable for food packaging, whereas Santos et al. [13] emphasised the potential of seafood-processing waste as a sustainable source of chitosan. Further research has focused on enhancing the overall performance of chitosan-based materials through improvements in mechanical strength and barrier properties, thereby accelerating the development of sustainable bioplastics derived from shrimp shell waste [7], [14].

Nevertheless, several important gaps remain in the existing body of knowledge. Most studies have been conducted at laboratory scale using shrimp shell waste collected from local markets, mixed seafood waste streams, or other non-traceable sources. As noted by Younes and Rinaudo [15], variations in raw material origin can significantly influence the quality and functionality of the resulting chitosan; however, relatively few studies have investigated this issue using materials sourced from traceable industrial supply chains. In parallel, extensive research has been devoted to advanced extraction technologies, including lactic acid fermentation, deep eutectic solvent extraction, and enzyme-assisted processing [13], [14], [16]-[18]. Despite these advances, limited attention has been given to establishing a clear connection between industrial waste streams and end-use material performance, particularly in the context of biodegradable packaging applications. Furthermore, although many studies have prioritised improving mechanical strength, comparatively less emphasis has been placed on understanding how moisture content and plasticisation behaviour influence the mechanical performance of chitosan films. This relationship is especially important for flexible packaging materials, where moisture-induced changes can directly affect material functionality and durability [8]. Consequently, the transfer of laboratory-scale findings into practical industrial applications remains limited.

To address these shortcomings, the present study adopts an industry-integrated approach by utilising shrimp shell waste obtained directly from a traceable commercial shrimp farm, representing a continuous and large-scale source of aquaculture waste. In contrast to previous studies, this approach establishes a direct link between industrial waste generation and material development, thereby improving the practical relevance and scalability of the research. The study aimed to extract chitosan from industrial shrimp shell waste and evaluate the functional performance of chitosan-based bioplastic films, with particular focus on moisture content and tensile strength. A key contribution of this work is the systematic investigation of the relationship between plasticisation behaviour and mechanical properties within a practical waste-to-material framework. By demonstrating the valorisation of industrial shrimp waste into biodegradable packaging materials, the study supports circular economy implementation in the aquaculture industry while contributing to the advancement of sustainable packaging technologies based on real industrial biomass.

2.0 Methodology

This study adopted an experimental approach to assess the feasibility of converting industrial shrimp shell waste into biodegradable bioplastic films. The work involved three main stages: the extraction of chitosan from shrimp shell waste, the preparation of chitosan-based bioplastic films using a solution-casting method, and the evaluation of the resulting films through physical and mechanical characterisation. The overall experimental framework employed in this study is presented in Figure 1.

As shown in Figure 1, the experimental procedure was carried out in four successive stages. First, chitosan was extracted from industrial shrimp shell waste through a series of demineralisation, deproteinisation, and alkaline deacetylation processes. The extracted chitosan was then used as the primary component in bioplastic film formulations, which were prepared using the solution-casting technique. Following film formation, a range of physical and mechanical properties was assessed, including film thickness, moisture content, tensile strength, elongation at break, and Young's modulus. Finally, the experimental results were statistically analysed and expressed as mean ± standard deviation based on triplicate measurements, allowing the influence of chitosan concentration on the performance of the developed bioplastic films to be systematically evaluated.

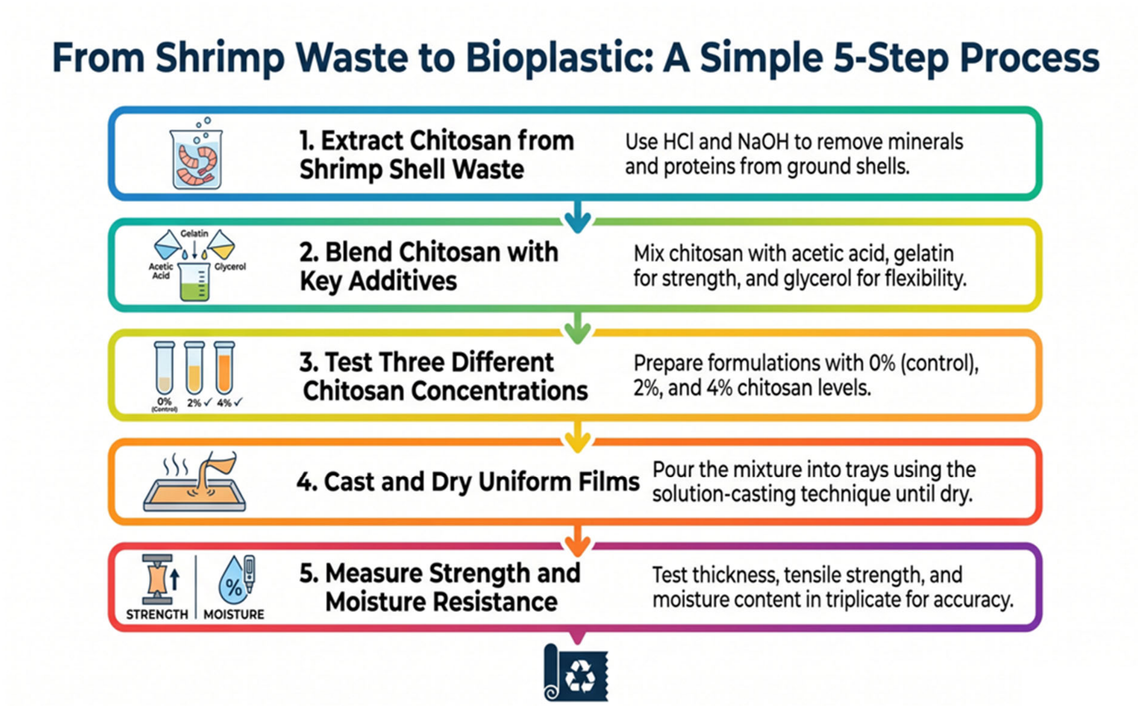


Figure 1: Overall experimental workflow for the preparation and characterisation of shrimp-shell-derived bioplastic films. Visualisation and conceptual layout generated using NotebookLM

2.1 Chitosan Extraction from Shrimp Shell Waste

Shrimp shell waste sourced from CPF Semporna Farm, Sabah, a subsidiary of Asia Aquaculture (M) Sdn. Bhd., served as the raw material for chitosan extraction. Prior to processing, the shells were thoroughly rinsed with distilled water to remove adhering impurities, dried in a hot-air oven, and milled into a fine powder. Chitin was then isolated through successive demineralisation and deproteinisation steps. During demineralisation, hydrochloric acid (HCl) was used to remove inorganic constituents, primarily calcium carbonate, while deproteinisation was carried out using sodium hydroxide (NaOH) to eliminate proteins and other residual organic matter. The purified chitin obtained from these treatments was subsequently converted into chitosan through alkaline deacetylation using a concentrated sodium hydroxide solution [13], [19].

The extraction process followed established chemical protocols widely employed for the recovery of chitosan from crustacean shell waste, owing to their proven effectiveness, operational simplicity, and suitability for large-scale implementation [15], [19]. The resulting chitosan was used directly in the preparation of bioplastic films. No additional characterisation was undertaken to determine its degree of deacetylation or molecular weight prior to film fabrication.

2.2 Preparation of Chitosan-Based Bioplastic Films

Bioplastic films were prepared using the solution-casting method, which is widely employed in the production of biodegradable films from natural polymers because of its simplicity, reliability, and ability to produce films with relatively uniform structures [12], [20]. To prepare the film-forming solution, the extracted chitosan was dissolved in 1% (v/v) acetic acid and continuously stirred using a magnetic stirrer until a clear and homogeneous solution was obtained. Gelatine was then incorporated as a co-film-forming polymer to improve film cohesion and structural integrity, while glycerol was added as a plasticiser to enhance flexibility and reduce brittleness [7], [8].

Three formulations were developed by varying the chitosan concentration at 0% (Sample A), 2% (Sample B), and 4% (Sample C) (w/v). Sample A served as the control formulation, containing only gelatine and glycerol, whereas Samples B and C included chitosan at concentrations of 2% and 4%, respectively. To ensure that any differences observed in film performance were primarily associated with chitosan content, the amount of glycerol was kept constant across all formulations. The resulting solutions were poured into rectangular casting trays and dried under controlled conditions until smooth, continuous, and uniform films were formed.

Each formulation was prepared independently in triplicate (n = 3) to ensure the reliability and reproducibility of the experimental results. After drying, the films were subjected to a series of physical and mechanical evaluations, including thickness measurement, moisture content determination, and mechanical property testing.

2.3 Film Thickness Measurement

The thickness of each bioplastic film was measured using a digital micrometre with an accuracy of ±0.001 mm. Measurements were recorded at five randomly selected locations on each specimen, and the mean value was taken as the representative film thickness. Maintaining similar thicknesses among the film formulations was essential to ensure that differences in moisture and mechanical properties could be attributed to variations in composition rather than differences in film dimensions [8], [11].

2.4 Mechanical and Moisture Characterisation

The mechanical properties of the prepared bioplastic films were characterised using tensile testing. Tensile strength, elongation at break, and Young's modulus were determined to provide insights into the strength, flexibility, and rigidity of the films [7], [12].

The moisture content of each film was measured using the gravimetric oven-drying technique based on the difference in sample mass before and after drying to a constant weight [8], [20]. All measurements were performed in triplicate ($n = 3$), and the data are presented as mean ± standard deviation to demonstrate the consistency and reproducibility of the experimental results.

3.0 Results and Discussion

3.1 Bioplastic Film

The chitosan extracted from shrimp shell waste was obtained as an off-white powder and dissolved readily in 1% (v/v) acetic acid, producing a homogeneous solution suitable for film preparation [21]. The bioplastic films produced were transparent, flexible, and possessed smooth, continuous surfaces, as illustrated in Figure 2. These observations indicate that the formulation components were successfully incorporated into the polymer network and resulting in films with a uniform appearance.

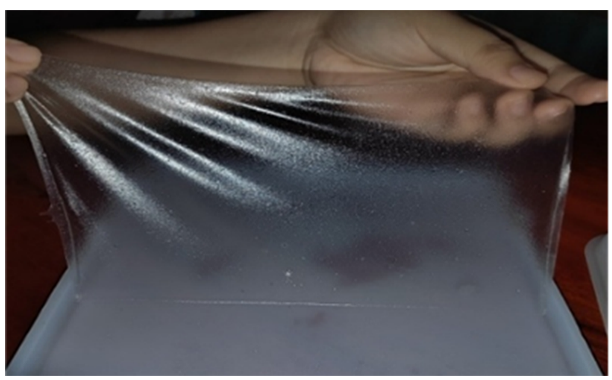


Figure 2: Bioplastic film made from shrimp shell

The high degree of transparency and overall uniformity suggests that the polymer constituents were well dispersed throughout the film matrix. Comparable characteristics have been reported in previous studies on chitosan-based films. Chabra et al. [10], for example, observed that films formulated with appropriate amounts of plasticiser generally exhibited good optical clarity together with satisfactory structural integrity. The flexibility of the films prepared in the present study is likely attributable to the presence of glycerol, which acts as a plasticiser by increasing polymer chain mobility and reducing brittleness [12]. Similar effects have also been documented by Jin et al. [11], who reported that glycerol promotes the formation of flexible biodegradable films with a homogeneous appearance.

In addition, the smooth and slightly glossy film surfaces suggest good compatibility among the formulation components, with little indication of phase separation during film formation. Favian and Nugraheni [8] reported similar observations, noting that chitosan-based films containing uniformly distributed polymer constituents tended to exhibit improved surface homogeneity. Although microstructural analysis was not performed in this study using techniques such as scanning electron microscopy (SEM), the macroscopic appearance of the films provides qualitative evidence of successful film formation and favourable interactions between the constituent materials.

3.2 Moisture Content and Tensile Strength Analysis

The mechanical and moisture-related properties of the shrimp-shell-derived bioplastic films are presented in Table 1. Tensile strength values ranged from 1.11 to 2.42 MPa, while elongation at break varied between 31.1% and 104.3%. Young's modulus ranged from 1.83 to 35.8 MPa, and moisture content was recorded between 16.02% and 25.15%. Overall, the results show that chitosan concentration had a pronounced effect on the performance of the developed films. Among the tested formulations, Sample B containing 2.0% chitosan exhibited the highest tensile strength (2.42 ± 0.08 MPa), indicating an improved capacity to withstand applied stress. In contrast, Sample C containing 4.0% chitosan displayed the highest elongation at break (104.3 ± 3.2%) together with the lowest Young's modulus (1.83 ± 0.20 MPa), reflecting enhanced flexibility and reduced stiffness. Sample A, which contained no chitosan, recorded the highest Young's modulus (35.8 ± 1.2 MPa), suggesting a comparatively rigid film structure.

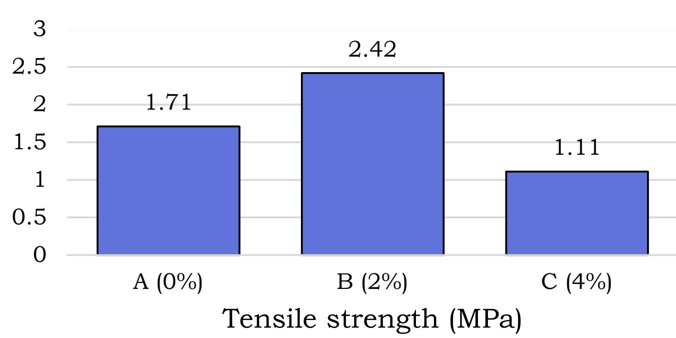
Table 1: Mechanical and moisture properties of shrimp-shell-derived bioplastic films with different chitosan concentrations

Property	Sample A (0.0% chitosan)	Sample B (2.0% chitosan)	Sample C (4.0% chitosan)
Tensile Strength (MPa)	1.71± 0.05	2.42± 0.08	1.11± 0.03
Elongation at Break (%)	64.1 ± 2.0	31.1 ± 1.5	104.3± 3.2
Young Modulus (MPa)	35.8 ± 1.2	27.7 ± 1.0	1.83 ± 0.2
Moisture Content (%)	25.15 ± 24.76	21.97 ± 1.78	16.02 ± 1.46

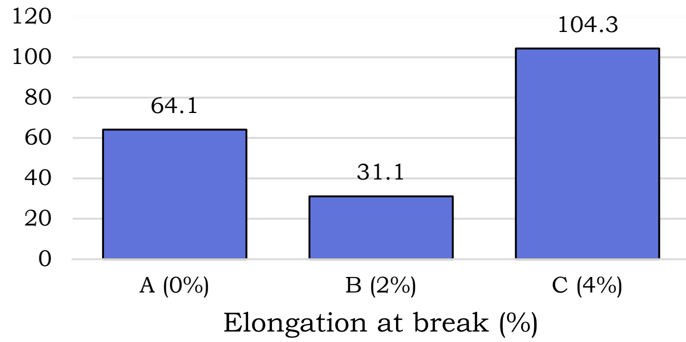
When compared with optimised chitosan-based films reported in previous studies, the tensile strength values obtained in the present work were relatively modest [22], [23]. Despite this limitation, the films demonstrated considerable extensibility, particularly Sample C, which exhibited the greatest elongation at break. The increase in elongation accompanied by a reduction in tensile strength indicates greater mobility of the polymer chains, enabling the films to undergo larger deformation before failure. Similar behaviour has been reported by Oyekunle et al. [7], who observed that increasing plasticiser content generally reduced tensile strength while improving elongation capacity. This trend reflects the commonly recognised balance between strength and flexibility in biodegradable polymer systems, where enhanced chain mobility promotes ductility but reduces resistance to tensile loading.

The effect of chitosan concentration on the mechanical properties and moisture content of the shrimp-shell-derived bioplastic films is presented in Figure 3. Overall, chitosan incorporation influenced tensile strength, elongation at break, Young's modulus, and moisture content, indicating changes in both matrix cohesion and polymer-chain mobility. The relatively high moisture content observed across the formulations suggests that water played an important role in determining film performance. In hydrophilic polymer systems, absorbed moisture can act as a secondary plasticiser by increasing molecular mobility and weakening intermolecular interactions within the polymer matrix [8]. Consequently, higher moisture content may reduce tensile strength and stiffness while promoting flexibility. This relationship was generally observed in the present study, where greater flexibility was accompanied by lower tensile strength and Young's modulus.

The tensile strength and elongation at break shown in Figures 3(a) and 3(b), respectively, indicate a trade-off between strength and flexibility among the formulations. The variation in Young's modulus in Figure 3(c) further supports this relationship. Sample A exhibited the highest Young's modulus of 35.8 MPa, indicating greater resistance to deformation and a relatively rigid structure. In contrast, Sample C recorded the lowest modulus of 1.83 MPa, suggesting a softer and more deformable material. This reduction in stiffness is consistent with the findings of Aranaz et al. [9], who associated similar behaviour with increased polymer-chain mobility and weaker intermolecular interactions within the polymer network. The substantial increase in elongation at break observed for Sample C further reinforces this interpretation, demonstrating that improved flexibility was accompanied by a corresponding decline in structural rigidity. The moisture-content results in Figure 3(d) provide further support for this interpretation, as absorbed water can facilitate polymer-chain movement and contribute to the observed reduction in stiffness.



(a)



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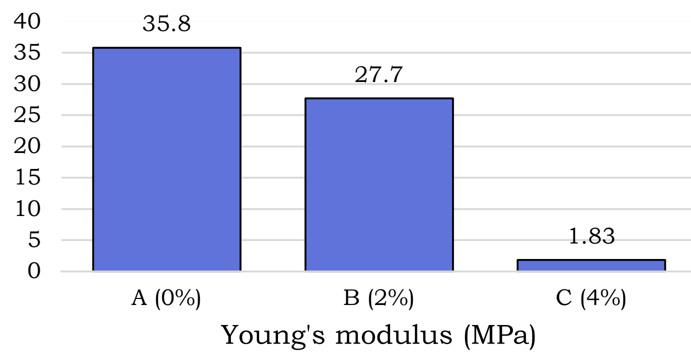
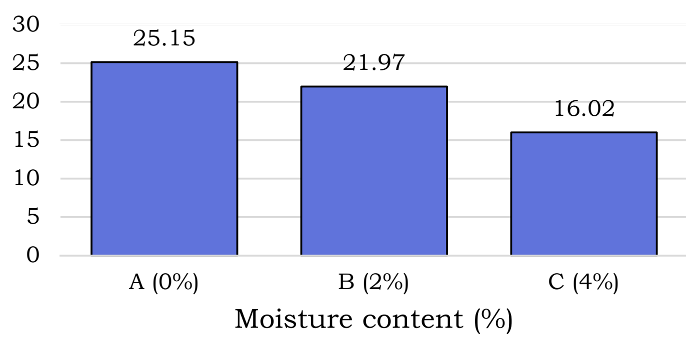


(c)



(d)

Figure 3: Effect of chitosan concentration on the mechanical properties and moisture content of shrimp-shell-derived bioplastic films: (a) tensile strength, (b) elongation at break, (c) Young's modulus, and (d) moisture content

Although the developed films demonstrated satisfactory flexibility and film-forming characteristics, their mechanical strength remained lower than that reported for several modified or reinforced chitosan-based films. Jiao et al. [14] reported that the incorporation of cross-linking agents and reinforcing fillers substantially improved tensile strength and moisture resistance. Likewise, Oyekunle et al. [7] demonstrated enhanced mechanical performance through optimisation of formulation parameters and processing conditions. These findings suggest that further improvements may be achieved by refining the chitosan content, adjusting the plasticiser concentration, or incorporating suitable reinforcing materials to strengthen the polymer matrix.

Overall, the findings demonstrate the feasibility of converting shrimp-shell waste into biodegradable bioplastic films with satisfactory film-forming characteristics and flexibility. While the current formulations may not yet provide sufficient mechanical strength for rigid or heavy-duty packaging applications, they show promising potential for use in flexible biodegradable packaging. Further optimisation of both formulation and processing conditions could improve the balance between strength, stiffness, and flexibility, thereby enhancing the practical applicability of bioplastic films derived from shrimp shell waste.

4.0 Conclusion

This study demonstrated that industrial shrimp shell waste obtained from CPF Semporna Farm, Sabah, can be successfully converted into chitosan-based bioplastic films through chemical extraction followed by solution casting. The extracted chitosan showed good film-forming capability, yielding films that were transparent, flexible, and visually uniform. The results revealed that chitosan concentration played a key role in determining the mechanical behaviour of the films. The formulation containing 2.0% chitosan achieved the highest tensile strength, while the 4.0% formulation exhibited the greatest elongation at break, indicating enhanced flexibility. These findings underline the importance of formulation design in balancing strength and flexibility to meet specific application requirements. Although the mechanical performance of the developed films remained below that reported for some optimised or reinforced chitosan-based materials, the films displayed favourable physical characteristics and sufficient flexibility for potential use in packaging applications where high mechanical loads are not required. More importantly, the study demonstrates a practical route for valorising traceable industrial shrimp shell waste into functional biodegradable materials, contributing to more efficient resource utilisation and supporting circular economy initiatives within the aquaculture industry. Further work should focus on comprehensive physicochemical characterisation of the extracted chitosan, including its degree of deacetylation and molecular weight, as these factors strongly influence material performance. Additional optimisation of formulation and processing conditions may help improve mechanical strength and water resistance. Future studies should also investigate biodegradation behaviour, barrier properties, and overall packaging performance to better assess the commercial viability of shrimp-shell-derived bioplastic films.

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Author Contributions

Norsyafiqa' Suhaimi: Conceptualisation, Methodology, Investigation, Formal Analysis, Writing – Original Draft, Writing – Review & Editing; **Asmahani Asmara**: Methodology, Investigation, Formal Analysis, Resources, Writing – Review & Editing; **Hazza Roshada Ramli**: Investigation, Data Curation, Formal Analysis, Resources, Writing – Review & Editing; **Azhar Ambo**: Conceptualisation, Supervision, Project Administration, Resources, Writing – Review & Editing; **Mohd Farhan Jamaluddin**: Conceptualisation, Project Administration, Resources, Supervision; **Kelvin Lim Huang Seng**: Funding Acquisition, Resources, Project Administration.

Conflicts of Interest

The manuscript has not been published elsewhere and is not under consideration by any other journal. All authors have reviewed and approved the manuscript, consent to its submission, and declare no conflicts of interest.

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