

Green and Sustainable Approaches for Chitosan Extraction: An Ecological Perspective on Marine Waste Management

Sasireka Rajendran*, Mohamed Himayathullah M, Muthu Selvan R, Linu Mithran Karthikeyan

Department of Biotechnology, Mepco Schlenk Engineering College (Autonomous), India

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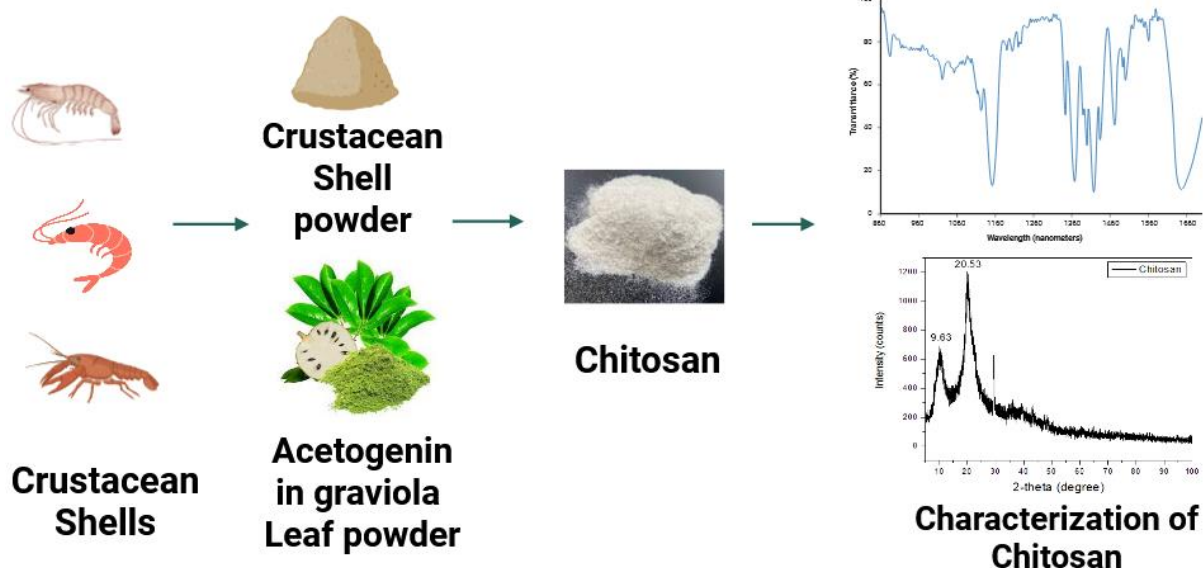
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Abstract Chitin, a valuable component, is present in crustacean shells and other sources and can be extracted via chemical and biological methods, and is subsequently deacetylated to produce chitosan, which possesses numerous applications in various fields. Though these techniques are efficient, owing to the drawbacks of ionic liquids and green solvent-mediated chitin extraction methods, they have been developed in recent years. Chitin extraction was focused on multiple strategies owing to its applicability. In this study, as an alternative approach, one-step extraction of chitosan is achieved, eliminating the deacetylation step. Using phytoextract-mediated extraction, chitosan was directly extracted without an intermediate chitin product. The Annonaceae family, specifically, *Annona muricata* (Graviola), rich in acetogenins, was utilized in this study to directly extract chitosan from its

source. Chitin extraction was efficiently carried out from various sources such as shrimp, prawn, and freshwater prawns. Chitosan's presence was determined by qualitative analysis, and the DNSA assay was used to quantify its amount. Similarly, FT-IR, XRD, and TGA/DTA studies were employed for chitosan characterization. The experimental results indicate the chitosan's presence, which aids in the possible recovery of chitosan directly from the sources using graviola leaf powder. This research indicates the potential recovery of chitosan from shells utilizing an acetogenin compound in the graviola leaves.

Keywords Chitin, Chitosan, Crustacean Shells, Acetogenins, Graviola

Graphical Abstract



1. Introduction

Chitin is a linear aminopolysaccharide composed of N-acetyl-D-glucosamine residues linked via β -(1 \rightarrow 4) glycosidic bonds, forming a highly stable and crystalline structure. It is the predominant component of crustacean exoskeletons such as shrimp, crabs, lobsters, and prawns, as well as in insects, fungi, and plankton [1]. Typically, chitin constitutes 15–40% of crustacean shell composition, while calcium carbonate and proteins account for 20–50% and 20–40%, respectively [2].

The seafood processing industry globally generates vast amounts of organic waste, with crustacean shells accounting for a major portion of the discarded biomass. Annually, millions of tonnes of shell waste are produced and commonly disposed of in landfills or coastal regions, resulting in significant environmental pollution and ecological imbalance. The uncontrolled accumulation of this organic material leads to odor emission, greenhouse gas release, and waste management challenges in coastal zones. Consequently, the abundant availability of crustacean shell waste presents a promising opportunity for its sustainable valorization through chitosan production, transforming an environmental burden into a valuable biopolymer [3].

Chitosan, the deacetylated derivative of chitin, is formed by removing the acetamide group from the polymer, yielding a product rich in amine functionalities [4]. While native chitin has limited applications, primarily in agriculture, chitosan exhibits enhanced solubility, reactivity, and functionality, enabling its use in biomedical, pharmaceutical, food, and environmental sectors [5]. Its favourable characteristics, biocompatibility, biodegradability, non-toxicity, and film-forming ability make it a versatile biopolymer with immense industrial

potential [6].

Conventionally, chitin and chitosan extraction involve demineralization, deproteinization, and deacetylation processes using concentrated acids and alkalis. Although effective, these methods are energy-intensive, generate hazardous effluents, and degrade polymer quality [7]. The use of strong reagents such as hydrochloric acid and sodium hydroxide leads to soil and water contamination, reduced molecular weight of chitosan, and high energy consumption due to prolonged heating. Additionally, valuable by-products such as calcium carbonate and proteins are often wasted, and handling corrosive chemicals poses safety hazards for workers.

Alternative eco-friendly methods, including enzymatic extraction and microbial fermentation, employ proteolytic enzymes and organic acids produced by microorganisms [8,9]. Although these techniques are sustainable and avoid toxic waste generation, they are often cost-prohibitive and less efficient at removing proteins and minerals on an industrial scale. Similarly, emerging green solvent-based systems such as Deep Eutectic Solvents (DES) and Natural Deep Eutectic Solvents (NADES) have shown promise for combined demineralization and deproteinization in a single step [10–12]. However, these systems require further optimization and economic evaluation for large-scale applications.

A promising recent development involves the use of acetogenin-based natural extracts for chitosan extraction. Acetogenins, the principal bioactive compounds of the Annonaceae family, possess strong chelating and enzymatic activity, facilitating both deproteinization and deacetylation [13]. Among various species, *Annona muricata* (Graviola or soursop) contains the highest acetogenin content (approximately 49%), surpassing *A. squamosa* and *A. suricata* [14]. Graviola is an evergreen

tropical tree widely distributed in Asia, Africa, and South America. Its leaves are rich in acetogenins, alkaloids, and phenolic compounds that exhibit antimicrobial, antioxidant, and cytotoxic properties [15,16]. In tropical regions such as southern India, Graviola is readily available and cultivated due to its medicinal significance and adaptability to warm, humid climates [17,18]. The leaves' biochemical richness and local accessibility make Graviola extract an excellent candidate for green extraction of chitosan from crustacean shells. The presence of acetogenins allows it to function as both a deproteinizing and deacetylating agent, simplifying the conventional multi-step process into a single, sustainable method.

Plant-based extraction approaches not only eliminate the need for hazardous chemicals but also reduce energy consumption and preserve chitosan's structural integrity. The use of renewable and biodegradable plant resources aligns with global trends in sustainable biotechnology and green chemistry, offering an environmentally responsible pathway for waste valorization. Integrating Graviola-assisted extraction into chitosan production supports the circular bioeconomy by converting seafood waste into high-value biopolymers, minimizing ecological impact, and enhancing economic sustainability. Therefore, the present investigation focuses on the recovery of chitosan using acetogenin-rich Graviola extract as a natural, green alternative to conventional chemical extraction methods. This study aims to explore its efficiency, scalability, and potential for sustainable industrial application, contributing to environmental conservation and waste management in coastal regions.

2. Experimental Section

2.1. Materials

Chitosan from shrimp shells (Himedia), Potassium hydroxide (KOH), Ethanol (100 %), Sodium potassium tartrate, Sodium hypochlorite (NaClO), Sodium hydroxide (NaOH), Glacial acetic acid (CH₃COOH), Sodium nitrite (NaNO₂), 3,5-dinitro salicylic acid (DNSA), Sulfuric acid (H₂SO₄), and Potassium bromide. Shells of Prawn, Shrimp, and Freshwater prawn were collected from Kerala, India. Graviola leaves were collected from Thandikudi village, Dindigul district of Tamil Nadu. Analytical grade chemicals were used for all experimental procedures.

2.2. Methodology

2.2.1. Sample Collection

The Graviola leaves were harvested during the early morning to maximize phytochemical content and minimize degradation. Leaves were collected from mature trees aged approximately 6 to 7 years. Mature leaves (approximately

2–3 months old) were selected to ensure consistent acetogenin levels. Leaves were collected from 6 individual plants, spaced apart to minimize chemotype variation and ensure extract uniformity.

2.2.2. Graviola Leaf Extraction

Collected leaves from the Graviola plant (*A. muricata*) were dried at room temperature for 2 to 3 days. The dried leaf material was blended into a fine powder and stored at room temperature. Initially, 4 g of dried powder was measured and suspended in 200 mL of double-distilled water. This mixture was boiled using a heating mantle. The boiling was continued until the volume of the mixture was reduced by half. Then, the extract was cooled and filtered using filter paper [19]. The extract obtained from Graviola leaves appeared dark green to olive brown. It had a mildly astringent, grassy odor characteristic of phenolic and acetogenin-rich herbal extracts. Filtrate was collected and used to extract chitosan from the crustacean shells (Figure 1).

2.2.3. Phytoextract-Mediated Chitosan Extraction

Shells obtained from prawn, shrimp, and freshwater prawns were thoroughly washed with tap water and shade-dried until completely devoid of moisture. The dried shells were subsequently pulverized into a fine powder using a blender. For the extraction of chitosan, 0.5 g of each powdered sample was surface-sterilized with 70% ethanol and added to 50 mL of graviola leaf extract. The mixtures were incubated in a water bath shaker at 70 °C for 24 hours with continuous agitation at 160 rpm. After incubation, the samples were centrifuged at 14,000 rpm for 45 min to isolate the pellet. The clear liquid above the pellet was removed and treated with a 1% sodium hypochlorite solution for decolorization. The decolorization step using 1% NaClO (sodium hypochlorite) was essential to remove the phytochemicals (e.g., chlorophyll, tannins, flavonoids) remaining in the pellet, which imparted dark brown coloration to the chitosan. Since the presence of residual pigmentation can interfere with spectroscopic (FTIR, UV-Vis) and thermal analyses (TGA/DTA) and may reduce product purity, the pellet was decolorized using 1% NaClO. Additionally, the step improves visual quality and helps confirm the extraction of colorless to off-white chitosan, as expected in its pure form. The pellet was washed with double-distilled water to remove residual NaClO solution [20]. Finally, the pellet was stored at 4 °C for further analysis (Figure 2).

2.2.4. Proposed Mechanism of Extraction of Chitosan

Acetogenins in the graviola extract contain hydroxyl groups (-OH) and γ -lactone structures that may facilitate nucleophilic attack on the acetyl group of chitin. Under mild heating (≈ 70 °C), these groups can break the amide bond and catalyze deacetylation, releasing acetic acid and forming a primary amine (-NH₂) group (Figure 3).

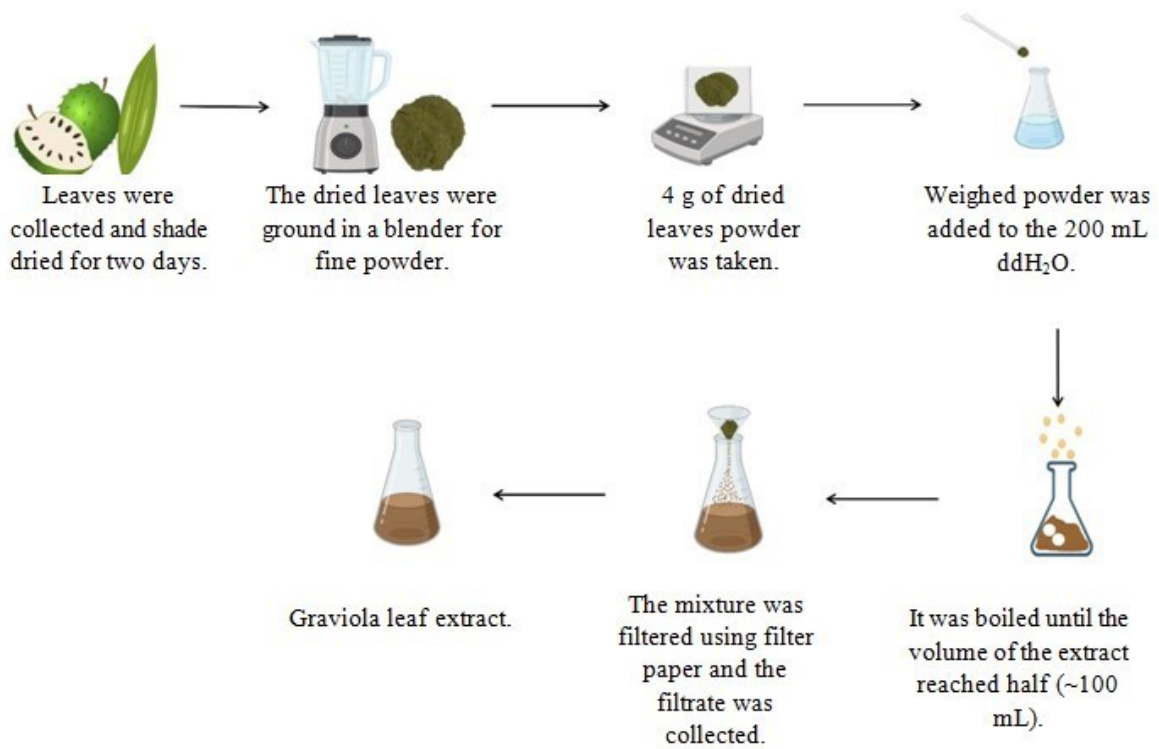


Figure 1. Graviola leaf extraction

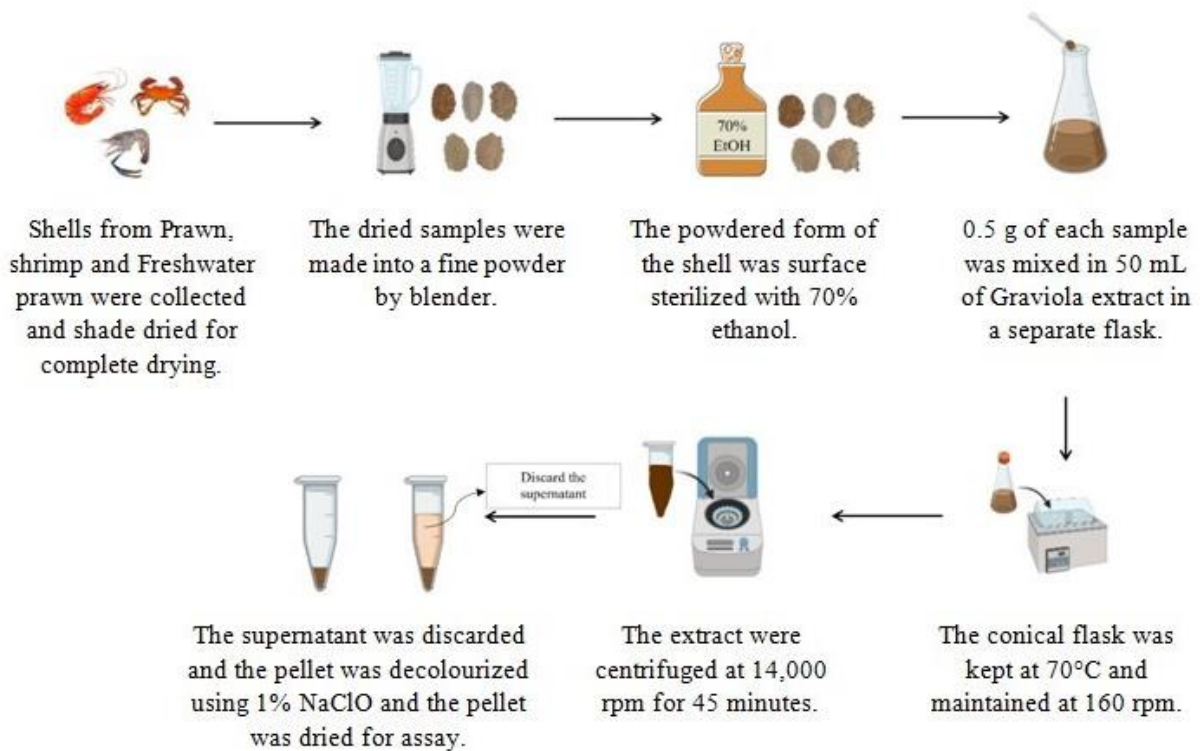


Figure 2. Phytoextract-mediated extraction

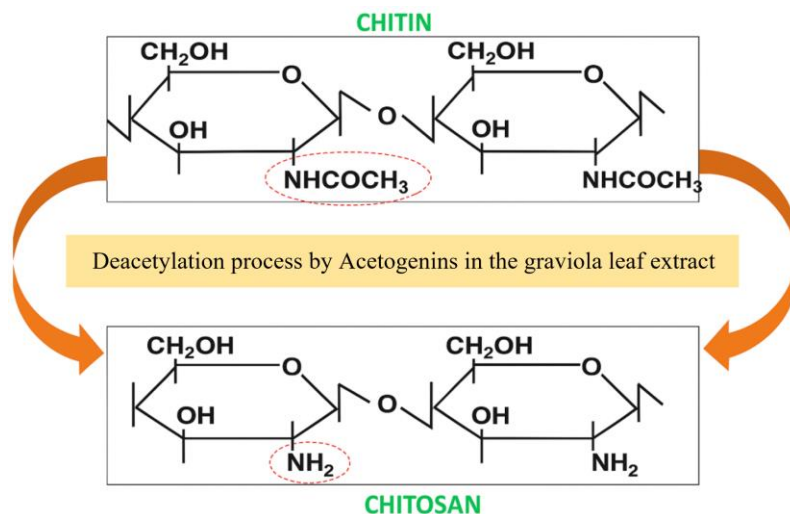


Figure 3. Proposed mechanism of deacetylation by acetogenins in the graviola leaf extract

2.2.5. Qualitative Assessment of Extracted Chitosan

To qualitatively detect chitosan, a chemical precipitation method was employed. A 2 mg quantity of the sample was transferred into a clean test tube, to which 3 mL of 1% potassium hydroxide was added. The mixture was kept in a water bath and heated to 75 °C for 60 minutes. After cooling, 2 mL of 3% glacial acetic acid was introduced and allowed to react for approximately 1 to 3 minutes. This was followed by the addition of a few drops of 1% sulfuric acid (H₂SO₄). The tube was then kept undisturbed for 2 hours. The development of a white precipitate confirmed the presence of chitosan in the sample [21].

2.2.6. Quantitative Determination of Chitosan

A stock solution of 3 mg/mL was created by dispersing chitosan in glacial acetic acid. A range of chitosan concentrations (0.2–3 mg/mL) was used in the preparation of the reaction mixture. To quantify chitosan, 0.1 mL of 0.5 M NaNO₂ was introduced to each test tube containing the sample solution. The mixtures were incubated in a water bath at 80 °C for 45 minutes. After the incubation period, the test tubes were removed and allowed to cool to room temperature naturally. Similarly, the efficiency of chitosan extraction by graviola leaf extract for different incubation times was also analyzed.

The dinitrosalicylic acid (DNSA) reagent was freshly made using 15 g of sodium potassium tartrate, 10 mL of 2 N sodium hydroxide (NaOH), and 0.5 g of DNSA in distilled water, with the final volume adjusted to 50 mL. Following reagent preparation, 1 mL was dispensed into each test tube to stop the reaction and incubated in a water bath at 75 °C for 15 minutes, and subsequently cooled for further spectrophotometric evaluation. Absorbance readings were taken at 540 nm, and a graph correlating absorbance to chitosan concentration was generated [22]. The reaction mechanism involved in the formation of the coloured product and spectrometric determination are highlighted in Figure 4. The deacetylation degree was also

calculated for further application.

2.2.7. Fourier Transform Infrared Spectroscopy (FT-IR)

FT-IR spectra of both standard chitosan and all samples were captured using a SHIMADZU spectrometer to discern their functional groups and chemical bonding. The samples were converted into powder form and mixed with KBr powder to create KBr pellets, which were then pressed. Spectral data were acquired in transmittance mode by averaging 75 scans over a wavenumber range of 4500 to 300 cm⁻¹, using a resolution of 16 cm⁻¹ [23].

2.2.8. X-Ray Diffraction (XRD)

The crystalline nature of chitosan extracted using graviola leaf extract was examined through X-ray diffraction (XRD). Measurements were carried out on a PANalytical X'Pert Powder Diffractometer, employing Cu K α radiation ($\lambda = 1.54 \text{ \AA}$) as the X-ray source. The instrument operated at 40 kV and 15 mA. Data acquisition was performed over a 2θ range of 2° to 80°, with a step interval of 0.02 ° and a scanning speed of 5 ° per minute. The diffraction profiles were used to evaluate the crystallinity of the chitosan samples.

2.2.9. Thermogravimetric / Differential Thermal Analysis (TGA/DTA)

Thermogravimetric analysis (TGA) monitors variations in the sample mass under a controlled environment influenced by time or temperature. This technique is useful for evaluating thermal stability, composition, and decomposition behavior of materials. Similarly, DTA evaluates the temperature difference between a test sample and a reference material while both are exposed to identical heating or cooling rates, providing insights into thermal transitions such as melting, crystallization, or decomposition. The change in weight and the difference in heat were recorded using TGA/DTA (Model: NJA – STA 2500 Regulus, NETZSCH) monitoring at 30°C to 500°C.

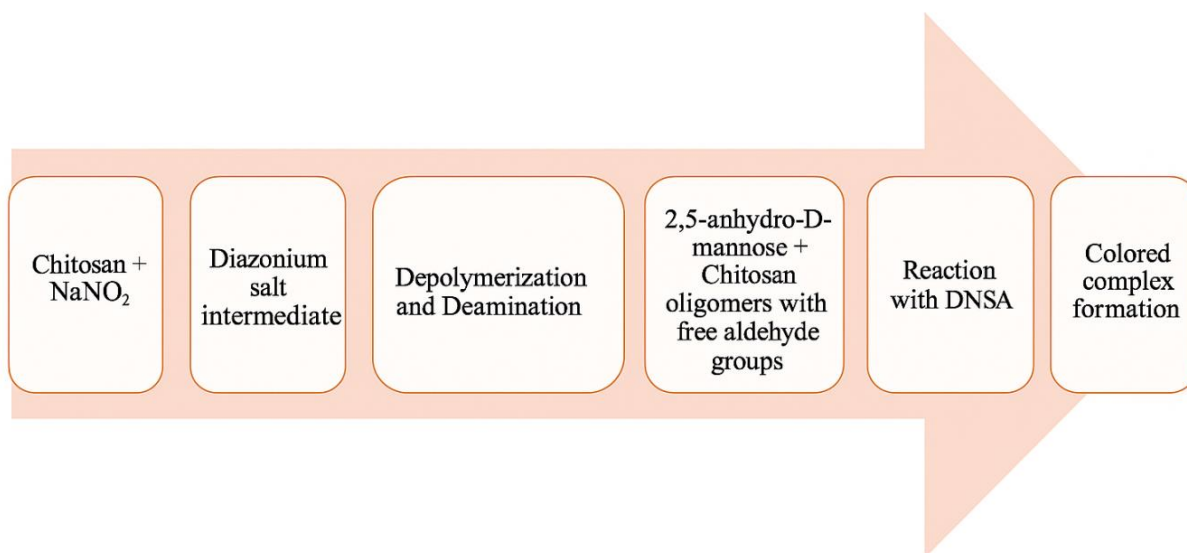


Figure 4. Reaction mechanism of the estimation of chitosan

3. Results

3.1. Qualitative Analysis of Chitosan

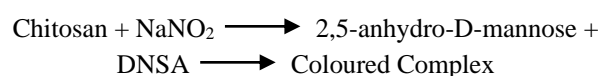
The presence of chitosan in the extracted samples was confirmed qualitatively by adding KOH solution, after which acetic acid was added to the test tube to ensure complete dissolution. Chitosan, soluble in an aqueous acidic environment, will precipitate upon the addition of acid. A few drops of sulfuric acid in the test tube make the dissolved chitosan, resulting in the formation of a white precipitate (Figure 5).

In a test tube containing standard chitosan (Figure 5 (a)), the formation of a white precipitate is readily observable, indicating the presence of chitosan. Similarly, when comparing the chitosan extracted from leaf extract samples with the standard, the presence of chitosan is confirmed by the visualization of the precipitate. The slight brown colour indicates the possibilities of pigments in the extracted chitosan, which is further focused on to improve the purity.

3.2. Quantitative Analysis of Chitosan

The quantitative assay facilitated the measurement of chitosan content in various crustacean sources. Samples extracted with phytoextracts were quantified, and the chitosan concentration in different sources was determined using a standard graph. In this assay, a standard concentration of 3 mg/mL was prepared to quantify the samples concentrations. To determine the chitosan concentration in the samples, a depolymerization method was employed. Initially, a weak base of NaNO_2 was added

to the test tube, initiating depolymerization at 80 °C through the deamination of chitosan's (1 → 4)-linked 2-acetamido-2-deoxy-β-D-glucopyranose units. This process led to the formation of 2,5-anhydro-D-mannose at the reducing end. The resulting reduced sugar was then subjected to analysis using the DNSA assay. Upon addition of DNSA, the reducing sugar reacted at 75 °C to form a coloured complex, which was subsequently spectrophotometrically analyzed at an absorbance of 540 nm. Then, the standard graph between the concentration of standard chitosan and OD at 540 nm was plotted (Figure 6).



Following the identification of chitosan's presence through qualitative analysis, the concentrations of the samples were subsequently quantified. In this context, the sample-leaf extract mixture was subjected to incubation for two distinct time intervals: one day and three days, by incubating the mixture for different durations to observe how the reactions evolve and determine any time-dependent effects or changes in the sample composition or properties. The DNSA assay quantified these two distinct time samples. The construction of the standard graph will help in determining the concentration of chitosan obtained from various samples (Table 1). The concentrations of each sample that was incubated for three days increased when compared to the concentrations of samples incubated for one day. The quantity of chitosan was higher in the shrimp compared to that in other sources. The deacetylation degree was found to be 90%.

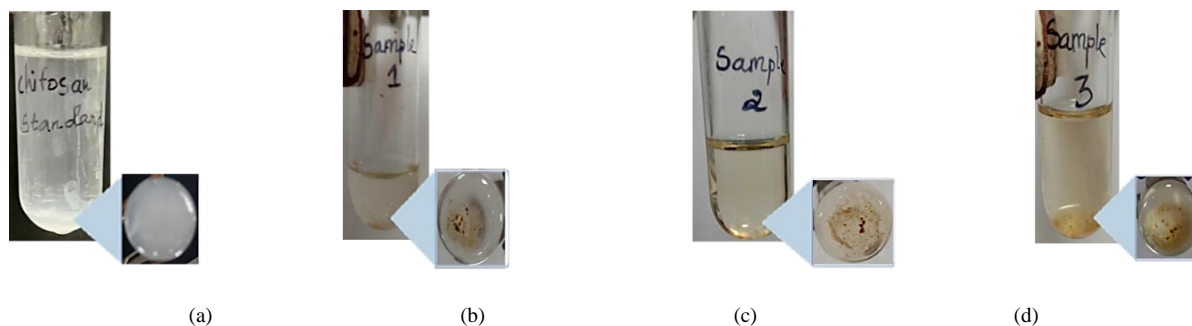


Figure 5. Qualitative analysis results of a) standard chitosan, b) prawn, c) freshwater prawn, and d) shrimp

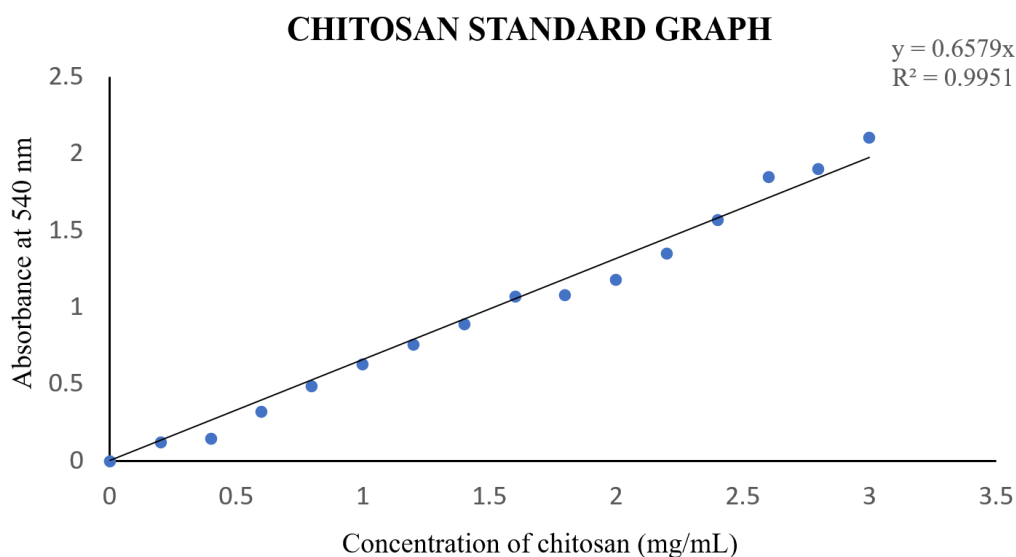


Figure 6. Standard graph for chitosan

Table 1. Comparison of the concentration of chitosan for two distinct times of incubation periods

Crustacean sources	Concentration of chitosan (mg/mL) (For one day incubation)	Concentration of chitosan (mg/mL) (For 3 days incubation)
Prawn	0.503	0.58
Shrimp	1.28	1.589
Freshwater prawn	0.32	0.433

3.3. Characterization of the obtained Chitosan

3.3.1. FT-IR Analysis

The samples extracted via phytoextract-mediated methods exhibit a characteristic FT-IR band for chitosan. For comparison, the FT-IR spectra of commercial chitin and chitosan from shrimp shells (Himedia) are also shown below. The commercial chitosan sample displayed a broad absorption region spanning 3600 to 3000 cm^{-1} , due to the combined stretching vibrations of hydroxyl ($-\text{OH}$) and amine ($-\text{NH}$) groups, along with contributions from intra- and intermolecular hydrogen bonding. A distinct peak

observed between 3400 and 3500 cm^{-1} confirms the presence of $\text{O}-\text{H}$ stretching, indicating hydroxyl groups integrated into the polymer structure. In conventional chitosan profiles, the $-\text{OH}$ and $-\text{NH}$ functional groups typically absorb at 3456 cm^{-1} and 3332 cm^{-1} , respectively. The absorption bands in the 3000 to 2850 cm^{-1} range correspond to $\text{C}-\text{H}$ stretching vibrations, with a prominent peak around 2893 cm^{-1} . A band at 1658 cm^{-1} was noted, corresponding to $\text{N}-\text{H}$ bending (amide I region) of primary amine groups. Additionally, the absorption near 1072 cm^{-1} was linked to $\text{C}-\text{O}-\text{C}$ stretching, reflecting the glycosidic bonds present in the chitosan framework (Figure 7).

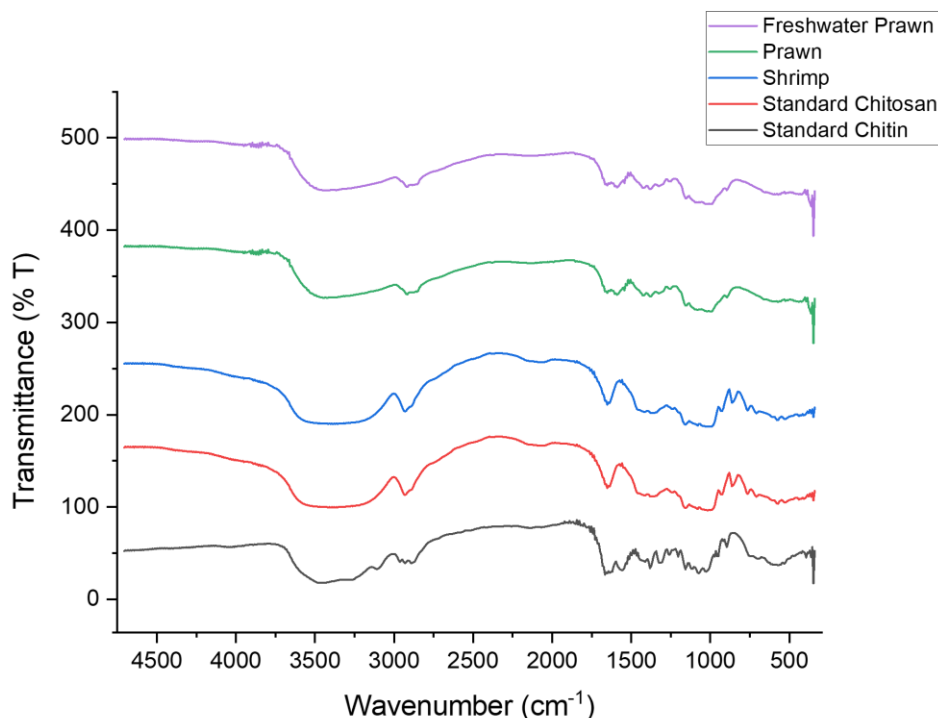


Figure 7. FT-IR spectra

The FT-IR analysis compared the results of phytoextract-mediated extraction with those of standard chitosan. Figure 7 illustrates the comparison between standard chitin, chitosan, and chitosan derived from various crustacean sources. The FT-IR spectrum of shrimp-derived chitosan shows a broad peak at 3441 cm^{-1} , corresponding to O–H stretching vibrations, while N–H stretching is detected at 3330 cm^{-1} . The C–H bond stretching appears near 2916 cm^{-1} . Characteristic chitosan peaks, including N–H bending and C–O–C bridge stretching, are observed at 1651 cm^{-1} and 1072 cm^{-1} , respectively.

Similarly, chitosan extracted from prawn shells exhibits a broad O–H stretching peak at approximately 3394 cm^{-1} , indicating the presence of hydroxyl groups. N–H stretching is recorded at 3294 cm^{-1} , and C–H stretching is consistent at 2916 cm^{-1} . The distinctive absorption bands for N–H bending and C–O–C bridge stretching are again noted at 1651 cm^{-1} and 1072 cm^{-1} , confirming typical chitosan functional groups.

The FT-IR spectrum of chitosan extracted from freshwater prawns revealed a broad absorption band centered at approximately 3425 cm^{-1} , corresponding to O–H stretching vibrations, and revealed hydroxyl functional groups. The N–H stretching vibration appeared at 3286 cm^{-1} , while C–H stretching was evident near 2924 cm^{-1} . Additional key peaks characteristic of chitosan were observed at 1651 cm^{-1} , attributed to N–H bending (amide region), and at 1072 cm^{-1} , which is due to the stretching of C–O–C linkages within the polysaccharide backbone [24]. The peaks of chitosan extracted from biological materials are highlighted in Table 2.

3.3.2. X-Ray Diffraction Analysis (XRD)

The phases and lattice configuration of materials are commonly characterized using XRD. The XRD patterns for standard chitin and chitosan exhibit distinct peaks at 9° and 19° , and 10° and 20° . A slight change in the peak from 9° to 10° and 19° to 20° indicates the deacetylated chitin. These peaks represent specific angles at which X-rays undergo diffraction by the crystalline structure of the chitosan material. Each peak corresponds to the reflection of X-rays of the atomic planes within the chitosan crystal lattice. The standard chitosan displays diffraction peaks at $2\theta = 9.9^\circ$ and 19.8° , as depicted in Figure 8. These peaks signify the presence of crystalline regions within the chitosan structure. The observation of diffraction peaks indicates that the chitosan possesses a semi-crystalline structure, meaning it consists of both crystalline and amorphous regions. This semi-crystalline nature is common in polysaccharide materials like chitosan, where some segments of the polymer chain arrange into ordered crystalline domains, while others remain disordered in the amorphous phase. Chitosan obtained from various crustacean sources reveals the presence of sharp peaks at approximately 10° and 20° , confirming its presence while being extracted using leaf extract rich in acetogenin. These diffraction peaks indicate the semi-crystalline nature of the chitosan samples [25].

3.3.3. Thermogravimetric / Differential Thermal Analysis (TGA/DTA)

The mass loss is indicated by the black curve, and the heat flow is represented by the red curve over the temperature range $200 - 400^\circ\text{C}$. A sharp peak denotes the

transition of the material (Figure 9). The TGA-DTA analysis of commercial chitosan and extracted chitosan exhibited an initial mass loss around 30–150 °C due to moisture evaporation. A major weight loss occurs between 250–350 °C, indicating thermal degradation of the chitosan polymer. The DTA curve shows a corresponding

endothermic peak near 100 °C (moisture loss) and a sharp exothermic peak near 300 °C (polymer decomposition). Residual mass (~30–35%) suggests the presence of carbonaceous or inorganic content. This confirms chitosan's thermal stability up to ~250 °C and its characteristic decomposition behavior.

Table 2. Comparison of FT-IR spectra of standard chitin, chitosan, and chitosan from crustacean sources

Functional group	Standard Chitin (cm ⁻¹)	Standard Chitosan (cm ⁻¹)	Prawn (cm ⁻¹)	Shrimp (cm ⁻¹)	Freshwater prawn (cm ⁻¹)
-OH	3448	3456	3394	3441	3425
N-H stretching	3300-3250	3332	3294	3330	3286
C-H stretching	2893	2893	2916	2916	2924
N-H bending	1680-1660	1658	1651	1651	1651
C-O-C stretching	1558	1072	1072	1072	1072

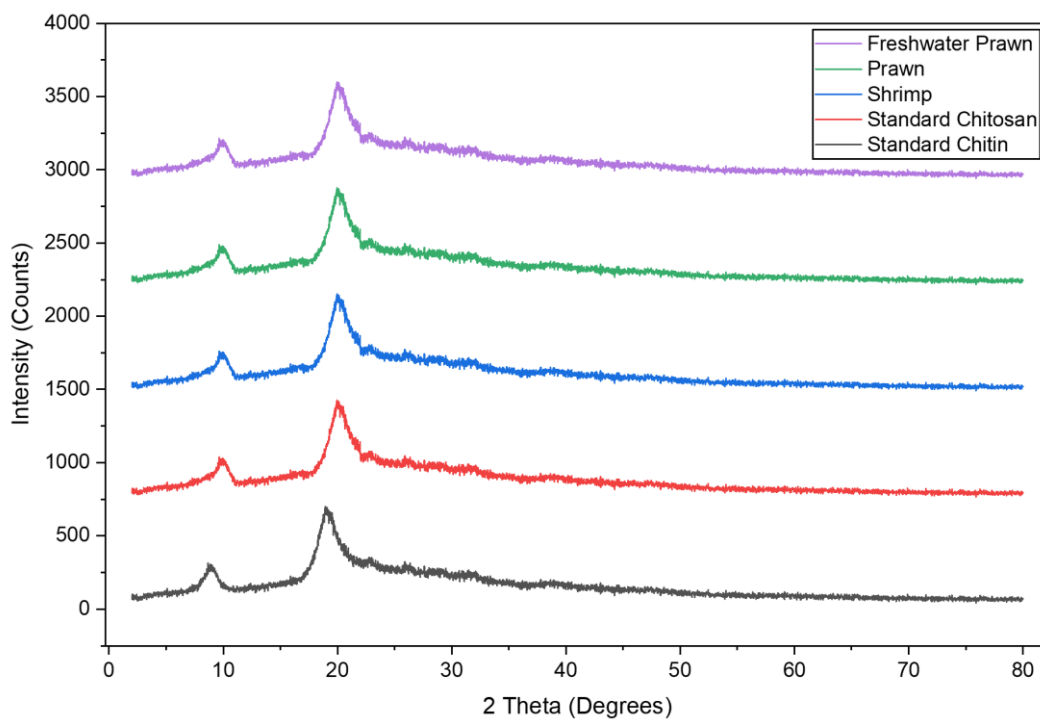


Figure 8. XRD profile of chitosan from crustacean sources

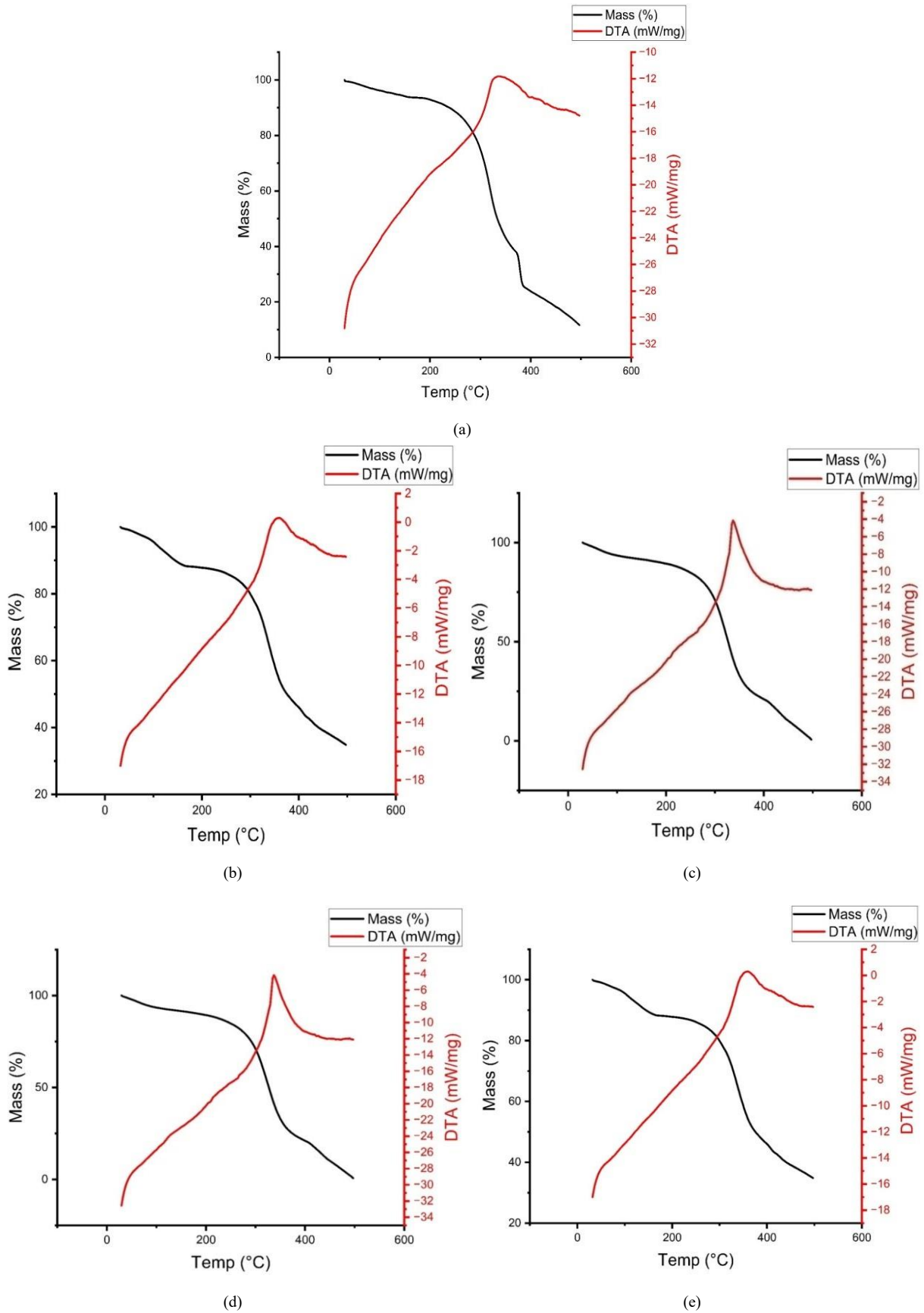


Figure 9. TGA/DTA analysis (a) Standard Chitin (b) Standard Chitosan (c) Chitosan from Prawn (d) Shrimp (e) Freshwater Prawn

4. Discussion

This study explores a sustainable, one-step extraction approach for obtaining chitosan directly from crustacean shells using *Annona muricata* (Graviola) leaf extract, rich in acetogenins. Traditionally, chitosan production involves the extraction of chitin followed by a deacetylation step using strong alkalis. Our proposed method eliminates the need for this intermediate step and harsh chemical conditions, significantly reducing environmental impact.

The FT-IR analysis of chitosan extracted from prawn, shrimp, and freshwater prawn shells displayed characteristic peaks comparable to commercial chitosan, confirming successful extraction. However, subtle spectral differences such as variations in the O-H and N-H stretching regions and CH deformation suggest slight structural differences due to the extraction medium. Notably, the broadening and shifting of OH peaks imply increased hydrogen bonding or residual plant components. XRD analysis revealed semi-crystalline structures in all samples, with diffraction peaks at 2θ around 9° and 19° , consistent with partially deacetylated chitosan. Compared to standard chitin, the observed crystalline peaks suggest successful conversion and reduction in acetyl groups, further confirming chitosan formation. Thermogravimetric and differential thermal analyses (TGA/DTA) highlighted key transitions, particularly weight loss around 200–300 °C, attributed to polymer degradation, and validated thermal stability. These results are in line with previous chitosan thermal profiles, indicating good material integrity post-extraction.

5. Conclusions and Future Directions

This study introduces a novel, eco-friendly approach for chitosan extraction from crustacean shells using *Graviola* (*Annona muricata*) leaf extract, effectively replacing the conventional multi-step chemical process. The acetogenin-rich phytoextract demonstrated dual functionality as both a deproteinizing and deacetylating agent, yielding high-quality chitosan with physicochemical characteristics comparable to commercial standards. Given the massive global generation of crustacean shell waste estimated at several million tonnes annually, this green extraction strategy presents a sustainable pathway for its valorization. The mild reaction conditions of the *Graviola*-based process minimize energy input, reduce the need for corrosion-resistant equipment, and enhance feasibility for industrial-scale operations. Its integration into existing seafood processing facilities can help transform shell waste into value-added biopolymers, contributing to a circular and low-carbon bioeconomy.

From a practical and policy perspective, implementing decentralized biorefineries in coastal regions could enable efficient shell waste conversion, reduce pollution, and create livelihood opportunities for local communities.

Encouraging governmental support, research–industry collaborations, and green technology incentives can further drive large-scale adoption. Future research should focus on optimizing extraction parameters, characterizing the degree of deacetylation using advanced analytical tools, and assessing biological functionalities such as antibacterial and antioxidant properties. Additionally, comprehensive evaluations of biocompatibility, scalability, and economic viability will be crucial for industrial translation. Overall, this study demonstrates that *Graviola*-assisted chitosan extraction not only advances sustainable biopolymer production but also offers a practical solution for marine waste management and environmental conservation.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contribution

Sasireka Rajendran – Manuscript writing, review, and editing, Mohamed Himayathullah – Manuscript original writing, Muthu Selvan R – Manuscript writing, Linu Mithran Karthikeyan – Supervision.

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