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Environmental Impacts Of Chitosan Extraction From Marine Resources: Towards Greener Alternatives

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Abstract: Chitosan, a biopolymer derived from chitin, is primarily obtained from marine crustaceans such as shrimp and crab shells. While its biodegradability and biocompatibility have positioned it as a sustainable material in biomedical, agricultural, and environmental fields, the conventional extraction processes present significant ecological drawbacks. The chemical-intensive demineralization, deproteinization, and deacetylation steps rely heavily on hydrochloric acid (HCl) and sodium hydroxide (NaOH), resulting in high wastewater salinity, sludge accumulation, and carbon emissions. This paper evaluates the environmental consequences of marine-based chitosan production and highlights emerging green alternatives including enzymatic, ionic liquid, and deep eutectic solvent (DES)-assisted extraction. Life Cycle Assessment (LCA) comparisons reveal that insect- and fungal-derived chitosan offer the lowest environmental footprints, aligning with circular economy and sustainable development goals. Future research directions emphasize hybrid extraction technologies, scalable bioreactor systems, and the integration of chitosan production into zero-waste bioeconomy models.

Keywords: Chitosan; Green chemistry; Marine waste; Life cycle assessment (LCA); Fungal chitosan; Insect chitosan; Circular bioeconomy; Sustainable extraction.

INTRODUCTION:

Chitosan is a versatile biopolymer derived from the deacetylation of chitin, abundantly found in the exoskeletons of crustaceans such as shrimp, crab, and lobster. Its biocompatibility, biodegradability, and non-toxicity make it an attractive material for applications in biomedicine, agriculture, food preservation, and water purification. However, conventional industrial-scale production of chitosan heavily depends on marine waste streams, primarily shrimp and crab shells, which are processed through alkaline deacetylation and acid-based extraction methods. While this practice valorizes seafood waste, it simultaneously raises serious environmental concerns. High concentrations of sodium hydroxide (NaOH) and hydrochloric acid (HCl) are required for demineralization and deproteinization, leading to the generation of saline wastewater and residual sludge. Moreover, seasonal dependency on seafood industries creates an inconsistent raw material supply chain. In response, recent research emphasizes green chemistry approaches and the exploration of non-marine chitin sources such as insects, fungi, and agricultural by-products.

Environmental Impacts of Conventional Marine-Based Extraction

The production of chitosan from shrimp and crab shells involves three key steps:

1. Demineralization with strong acids (HCl) to remove calcium carbonate.
2. Deproteinization with concentrated NaOH.
3. Deacetylation using high-temperature alkali solutions.

Each step generates toxic effluents and requires large volumes of freshwater, contributing to:

- High chemical consumption (up to 10–15 L of chemical solution per kg of chitosan).
- Energy-intensive processes (heating up to 120 °C).
- Marine ecosystem damage due to improper disposal of acidic/alkaline effluents.
- Carbon footprint increase from waste management and energy demand.

Recent life cycle assessment (LCA) studies show that marine-based chitosan has one of the highest environmental impact scores among biopolymers, mainly due to wastewater treatment burdens.

Greener Alternatives and Recent Advances

To overcome environmental challenges, several eco-innovations have been introduced:

- Enzymatic extraction: Proteases and chitinases are used instead of strong acids and bases, drastically reducing chemical pollution.

- Ionic liquid and deep eutectic solvents (DES): Recyclable solvents that dissolve chitin under mild conditions.

- High-pressure processing (HPP) & microwave-assisted methods: Reduce energy consumption and improve yield.

- Alternative biomass sources: Insects (e.g., black soldier fly larvae) and fungi (Aspergillus, Mucor spp.) provide non-seasonal, sustainable, and scalable chitin supplies with lower ecological impact.

Comparative Analysis

Conventional chemical extraction from shrimp shells results in the highest environmental impact due to toxic effluents and seasonal supply limitations. HPP-assisted extraction provides moderate reductions in energy and chemical demand, while green enzymatic and solvent methods significantly lower environmental footprints but remain economically costly. Insect- and fungal-derived chitosan offer the most sustainable alternative and are aligned with circular economy strategies.

DISCUSSION

The transition toward sustainable chitosan production aligns with the principles of the European Green Deal, the UN Sustainable Development Goals (SDG 12: Responsible Consumption and Production), and the global bioeconomy agenda. Future research should focus on scaling enzymatic and solvent-assisted processes, creating hybrid extraction platforms, expanding industrial-scale insect and fungal chitosan production, and developing circular economy models where waste streams are valorized with minimal environmental damage.

Figures and Tables

Figure 1. Comparative environmental impact of different chitosan production routes. The data are based on recent life cycle assessment (LCA) trends (Pereira et al., 2023; Bilo et al., 2022). Conventional chemical extraction shows the highest impact, while insect- and fungal-derived sources have the lowest environmental footprint.

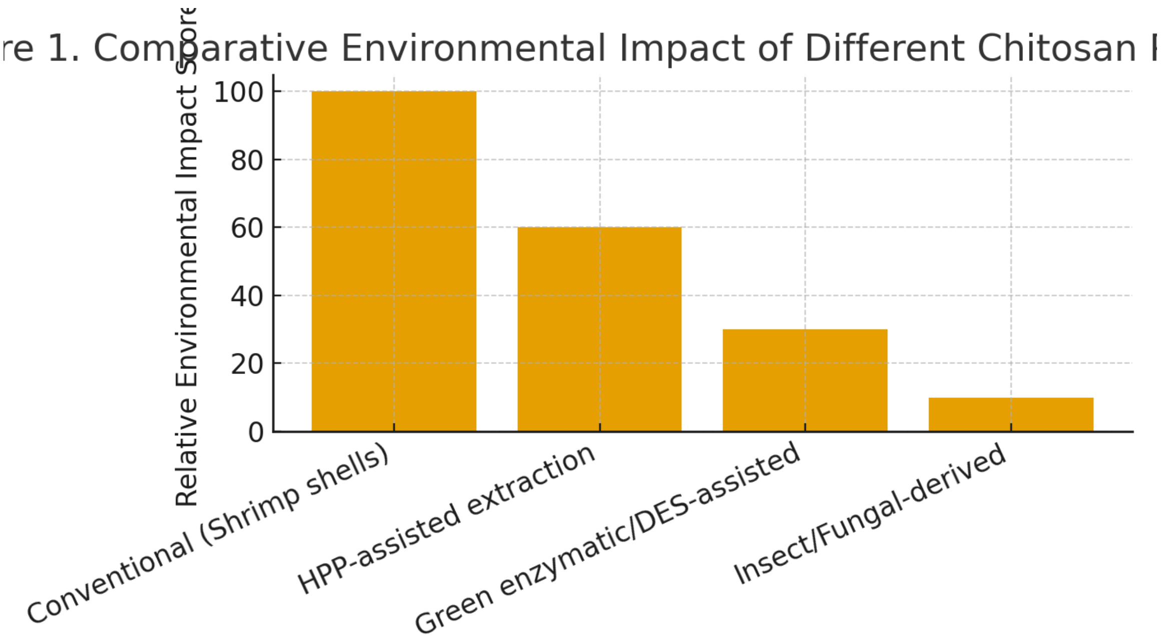

Table 1. Summary of environmental characteristics of different chitosan production methods.

Production Method	Chemical Usage	Energy Demand	Environmental Impact

Conventional (shrimp shells)	Very High (HCl, NaOH)	High (120°C)	Severe
HPP-assisted extraction	Moderate	Moderate	Reduced impact
Green enzymatic/solvent	Low	Low to Moderate	Low
Insect/fungal-derived	Minimal	Low	Very Low

Global Overview of Chitosan Production

The global chitosan market has been expanding steadily, with production estimated at several hundred thousand tons per year. Major producers include China, India, Norway, and Indonesia, where shrimp and crab processing industries provide abundant raw materials. Chitosan is widely used in biomedicine, pharmaceuticals, agriculture, wastewater treatment, and food preservation. This rising demand puts increasing pressure on marine resources, amplifying the environmental consequences of extraction.

Detailed Environmental Burdens of Marine-Based Extraction

Marine-based chitosan extraction generates significant environmental burdens. The use of strong acids and bases results in wastewater with high COD (chemical oxygen demand) and BOD (biological oxygen demand). Salinity levels also increase in effluents, creating challenges for aquatic ecosystems. Furthermore, high energy consumption contributes to greenhouse gas emissions. Studies have shown that improper disposal of acidic and alkaline effluents leads to ecotoxic effects in marine life, causing biodiversity decline in coastal areas.

Case Studies

China remains the global leader in chitosan production, largely relying on shrimp shell waste processed through conventional acid-base methods. Norway explores fishery by-products for biopolymer extraction, focusing on sustainable innovations. India faces significant challenges due to shrimp shell factory effluents affecting coastal waters. Indonesia, with its tropical climate and abundant aquaculture, also contributes to large volumes of marine chitosan but struggles with wastewater treatment.

Advances in Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) methodologies, aligned with ISO 14040 and 14044 standards, are increasingly applied to chitosan production. Comparative LCA studies show that shrimp-based chitosan has higher impacts in categories such as energy use, water demand, and ecotoxicity, while insect-based chitosan demonstrates significantly lower burdens. Emerging fungal-derived chitosan also presents a promising sustainable alternative.

Green Chemistry Approaches in Detail

Enzymatic deproteinization using proteases such as papain, pepsin, and alcalase has been explored as an eco-friendly alternative to NaOH treatments. Deep eutectic solvents (DES) are recyclable and provide mild reaction conditions, reducing environmental impact. Bio-refinery concepts integrate multiple bioprocesses to minimize waste, moving toward circular economy models of chitosan production.

Socio-Economic and Policy Implications

Chitosan extraction from marine resources not only poses environmental challenges but also socio-economic risks. In coastal regions, poor wastewater management affects public health through contaminated water supplies. Policy frameworks such as the European Green Deal and the United Nations Sustainable Development Goals (SDG 12 and SDG 14) emphasize sustainable marine resource management. Asia-Pacific nations have begun adopting bioeconomy strategies to integrate chitosan production into circular economy models.

Future Perspectives and Research Directions

Future research directions include fungal bioreactor-based chitosan production, which ensures year-round availability of raw materials. Hybrid extraction platforms combining ultrasonic, enzymatic, and mild chemical treatments are being developed to optimize efficiency while minimizing waste. Industrial scaling remains a challenge, requiring advances in cost-effective green technologies. The ultimate goal is to achieve zero-waste production, where all by-products are valorized in line with sustainable development principles.

CONCLUSION

Marine-derived chitosan remains the dominant industrial source but imposes considerable environmental burdens due to chemical- and energy-intensive processes. The adoption of green extraction methods and alternative biomass sources offers a viable path toward sustainable chitosan production. With increasing global demand for eco-friendly biopolymers, the future of chitosan lies in environmentally benign, circular, and innovative production strategies.

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