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Environmental Impact of Shrimp Processing Industries and Mitigation Strategies: A Path toward Circular Economy and Bio-valorization

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Abstract

Global seafood production generates significant volumes of organic waste, with approximately 6 to 8 million tons produced annually. The shrimp processing sector is uniquely waste-intensive, as 40-60% of the total shrimp weight is discarded as inedible heads and endoskeleton shells. In the Indian organized sector, this waste volume grew at a rate of 12% annually between 2000 and 2018, generating between 1.2 and 4.6 lakh tons annually. If managed unscientifically, these discards represent a severe environmental burden characterized by high organic loads in wastewater and greenhouse gas emissions from landfills. This paper evaluates the environmental impacts of shrimp processing, introduces a five-stage wastewater classification, and proposes mitigation strategies centered on biological treatment and "wealth from waste" valorization into high-value bioactive products like chitin and chitosan.

Introduction

The shrimp processing industry is a vital component of the global food sector, fueled by a per capita seafood consumption that rose from 9 kg in 2018 to 20.5 kg in 2020. India has emerged as a central player in this market, currently ranking as the 5th largest exporter of fish and fishery products globally. Within the Indian context, shrimp products are the dominant contributor to seafood exports; in 2022-23, India exported 7.2 lakh tons of frozen shrimp, accounting for approximately 45% of the total export quantity. However, this economic success is accompanied by a massive environmental challenge. Shrimp processing is uniquely waste-intensive, as 40-60% of the total shrimp weight is discarded as inedible heads and endoskeleton shells. In the Indian organized sector, the volume of shrimp processing waste grew at a compound rate of 12% annually between 2000 and 2018, with annual generation ranging from 1.2 to 4.6 lakh tons. When managed unscientifically, these discards create a significant **environmental and health nuisance** for both terrestrial and aquatic inhabitants, potentially leading to disease outbreaks and severe pollution.

Key environmental concerns include:

- **High Pollutant Loads:** Processing effluents carry high levels of **Biochemical Oxygen Demand (BOD)** and **Chemical Oxygen Demand (COD)**, particularly from stage 3 operations like cooking and canning.
- **Atmospheric Impact:** Decomposition of solid waste in landfills generates greenhouse gases such as **methane**, along with odorous compounds like **ammonia and hydrogen sulfide**.
- **Regulatory Pressures:** In India, the **Aquaculture Authority** and **Coastal Regulation Zone (CRZ)** notifications mandate strict guidelines for effluent treatment to protect fragile coastal ecosystems.

Despite these risks, modern research identifies shrimp waste as a "treasure" of biomolecules rather than a liability. These discards are abundant in **proteins (up to 65% in head waste), lipids, carotenoids (astaxanthin), and minerals**. Most notably, they are a primary source of **chitin**, a versatile polysaccharide with applications in the pharmaceutical, agricultural, and textile industries. This research focuses on the **"Wealth from Waste"** concept, exploring how valorizing these byproducts can mitigate environmental damage while meeting a global chitin demand projected to reach **$2,492 million by 2027**.

Literature Review and Background

1 Classification of Wastewater Recent reviews introduce a structured **five-stage classification** of seafood processing wastewater (SPW) based on operational procedures: initial washings (stage 1), filleting (stage 2), cooking and canning (stage 3), final washings (stage 4), and combined discharge (stage 5). Research indicates that **stage 3 wastewater** contains the highest concentrations of BOD, COD, total nitrogen, and oils, followed by stage 2, while stages 1 and 4 carry lower pollutant loads.

2 Environmental and Atmospheric Impact Direct disposal of these high-organic effluents into aquatic environments leads to **oxygen depletion, eutrophication, and biodiversity alteration**. When solid wastes are disposed of as landfills, their decomposition generates methane, hydrogen sulfide, and ammonia, which disrupt climatic conditions more than other waste removal processes. Furthermore, anaerobic conditions during storage can produce odorous **mercaptans**.
3 Composition and Potential of Waste Shrimp waste is rich in **-chitin**, the most stable allomorph where chains are arranged in parallel and opposite directions held by strong hydrogen bonds. Beyond chitin, these discards contain approximately **57.92% crude protein** and 19.10% fat on a dry weight basis.

Methodology
Mitigation strategies follow a dual approach of advanced wastewater management and bio-valorization.
1 Wastewater Management: Effluent Treatment Systems (ETS) The **Coastal Aquaculture Authority** mandates an ETS for farms exceeding 5 hectares within the CRZ. A modular ETS requires **10% of the total cultivable area** and comprises:
1. **Settlement Ponds:** Designed to trap **90% of solids** from harvest discharge.
2. **Bio-Ponds:** Utilizing **bio-remediation** with seaweeds (*Ulva latuca*) to reduce nutrient loads and filter-feeding molluscs (*Perna viridis*) to remove particulate matter.
3. **Aeration Ponds:** Utilizing mechanical aerators to increase dissolved oxygen and oxidize remaining organic matter.

2 Waste Valorization: Extraction Methods Two primary pathways for extracting chitin and chitosan are utilized:
- **Chemical Extraction:** Involves **deproteinization** using NaOH and **demineralization** with HCl. While fast and economical, it produces chemical-heavy effluents and can impair the physiochemical properties of the final polymer.
- **Biological Extraction:** Employs **proteolytic enzymes** (e.g., Alcalase) or **Lactic Acid Bacteria (LAB) fermentation**. This "green chemistry" approach is energy-efficient, eco-friendly, and maintains higher molecular weights in the extracted chitin.

Results
1 Indian Context Findings In India, only **25% of generated shrimp processing waste** is currently utilized, while 75% remains unused or is managed unscientifically. Current waste levels could produce **6,712 to 27,453 tons of chitin annually**. Forecasting suggests that by 2025, India will generate between **4.95 and 9.78 lakh tons** of shrimp waste, representing a massive secondary raw material pool.
2 Technical Efficacy
- **Bioconversion:** Successive two-step fermentation using *Lactobacillus rhamnoides* and *Bacillus amyloliquefaciens* achieved **97.5% demineralization** and **96.8% deproteinization** of shrimp shells.
- **Heavy Metal Remediation:** Chitosan derivatives demonstrated the capacity to remove **99.9% of Copper (II) and Silver (I)** from contaminated industrial streams.

Discussion
1 Resource Efficiency and Circular Economy Transitioning shrimp waste from "discard" to **"secondary raw material"** is essential for a circular economy. Chitin and chitosan have demonstrated high utility in **drug delivery, wound healing, and industrial wastewater treatment**. Integrating waste recovery into the industrial chain reduces disposal costs (which can be as high as $150/ton in some regions) and prevents public health disturbances.
2 Barriers to Implementation in India
- **Infrastructure:** Chitin-producing plants are too few to accommodate the generated waste volume.
- **Economic Bottlenecks:** High initial investment for specialized Effluent Treatment Plants (ETP) and extraction technology hinders entrepreneurship.
- **Quality Control:** Waste is often collected without assessing quality; there is an urgent need for **Standard Operating Procedures (SOP)** for icing, storage, and transportation.

Conclusion
The shrimp processing industry stands at a threshold where sustainability must drive economic expansion. While chemical extraction remains the industrial standard, the transition toward **biological extraction and "green chemistry"** is necessary to minimize environmental footprints and preserve bioactive properties. Future efforts must focus on **centralized collection systems**, product diversification into agricultural stimulants and biofuels, and government support to overcome infrastructure barriers.

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Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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