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Risk-Based Green Production Strategy for Chitosan in Medium-Scale Industry: An Integrated HAZOP, FMEA, and Environmental Performance Analysis

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Abstract

The production of chitosan in medium-scale industries is still highly dependent on hazardous chemicals and energy-intensive processes, leading to significant environmental impacts and occupational safety risks. This study aims to develop a risk-based green production strategy for chitosan by integrating Hazard and Operability Study (HAZOP), Failure Mode and Effect Analysis (FMEA), and environmental performance assessment. The research was conducted using a quantitative–descriptive approach based on baseline production data from a medium-scale chitosan process with a capacity of 10 kg of raw material per batch.

The results show that the total processing time reached 16 hours per batch with a chitosan yield of 26%. Chemical consumption remained relatively high, at 0.075 kg NaOH/kg raw material and 0.11 kg HCl/kg raw material, generating 80 L of liquid waste per batch with extreme pH values. Risk analysis identified deproteinization and demineralization stages as critical control points, with Risk Priority Number (RPN) values of 112 and 96, respectively, indicating high operational risk. Environmental performance analysis revealed energy consumption of 6.9 kWh/kg chitosan and water consumption of 61.5 L/kg chitosan.

The findings demonstrate that integrating risk mitigation with green production principles provides a systematic basis for reducing chemical usage, improving process safety, and enhancing environmental efficiency. This study contributes a practical baseline framework for sustainable chitosan production in medium-scale industries and supports the transition toward green and safer industrial practices.

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1. Introduction

Chitosan is a versatile biopolymer derived from chitin, widely recognized for its biodegradability, biocompatibility, and non-toxicity. Its applications span food preservation, pharmaceuticals, water treatment, bioplastics, and green packaging industries (Kumar, 2000) [18]; (No and Meyers, 2007) [21]; (Kumar and Negi, 2017) [17]. The increasing demand for sustainable materials has positioned chitosan as a strategic material in the transition toward green and circular industrial systems.

In Indonesia and other developing countries, chitosan production is predominantly conducted by small- and medium-scale industries that utilize seafood processing waste, particularly shrimp and crab shells, as raw materials (Zikri and Salamah, 2018) [32]. From a circular economy perspective, this practice contributes to waste valorization and resource efficiency (Geissdoerfer *et al*., 2017) [8]; (Korhonen *et al*., 2018) [15]. However, despite its environmental potential, the production process of chitosan remains highly dependent on hazardous chemicals such as hydrochloric acid (HCl) and sodium hydroxide (NaOH), leading to significant environmental burdens, chemical waste generation, and occupational safety risks (Wang *et al*., 2021) [29]; (Chou *et al*., 2020) [6].

Medium-scale manufacturing industries play a dominant role in Indonesia's industrial sector, accounting for a substantial proportion of employment and economic activity (BPS, 2021) [4]. Nevertheless, these industries often face structural limitations, including low technological adoption, limited risk management capacity, and inadequate occupational safety systems (ILO, 2019) [11]; (Islam *et al*., 2019) [12]. In chemical-based production systems such as chitosan manufacturing, these limitations increase the likelihood of process deviations, chemical exposure, and inefficient resource use.

Risk mitigation has therefore become a critical element in achieving sustainable chemical production. Established methodologies such as Hazard and Operability Study (HAZOP) and Failure Mode and Effect Analysis (FMEA) have been widely applied to identify, evaluate, and prioritize process-related risks in chemical and pharmaceutical industries (Khan and Abbasi, 1998) [13]; (CCPS, 2008) [5]; (Stone *et al*., 2020) [28]; (Yang *et al*., 2019) [30]. Previous studies have demonstrated that integrating HAZOP and FMEA can significantly enhance process reliability and safety performance (Lee *et al*., 2019) [19]; (Sharma *et al*., 2020) [26]. However, in the context of chitosan production, most studies focus on chemical optimization or product quality, while systematic risk-based approaches remain limited. In parallel, efforts to improve sustainability in chitosan production have emphasized process optimization, green solvents, and enzymatic extraction techniques to reduce chemical consumption and environmental impacts (Kumar and Mehta, 2019) [16]; (Liu *et al*., 2020) [20]; (Zhang *et al*., 2021) [31]. Life Cycle Assessment (LCA) has also been employed to evaluate environmental and economic impacts of chitosan production systems (Gupta *et al*., 2018) [9]; (Chou *et al*., 2020) [6]. While these approaches provide valuable insights into environmental performance, they are often disconnected from occupational safety and operational risk considerations, particularly in medium-scale industries.

From a systems perspective, macroergonomics and Total Quality Management (TQM) emphasize the integration of human, technological, and organizational elements to improve operational efficiency and safety simultaneously (Hendrick, 2001) [10]; (Kleiner, 2006) [14]; (Oakland, 2014) [22]. Studies in small- and medium-scale manufacturing have shown that ergonomic interventions and structured management systems can significantly improve productivity and reduce work-related risks (Smith *et al*., 2020) [27]; (Sharma *et al*., 2020) [26]. Nevertheless, such integrative approaches have rarely been applied to chemical-based biopolymer production systems.

Based on the above discussion, a clear research gap can be identified. Existing studies on chitosan production predominantly address chemical optimization and environmental performance, while limited attention is given to the integration of risk mitigation, occupational safety, and environmental efficiency within a unified production strategy, especially for medium-scale industries. This gap highlights the need for a comprehensive, risk-based framework that aligns green production principles with process safety and operational realities.

Therefore, this study aims to develop a risk-based green production strategy for chitosan by integrating HAZOP, FMEA, and environmental performance analysis. Using baseline production data from a medium-scale chitosan process, this research identifies critical risk points, evaluates chemical and resource consumption, and proposes strategic directions to improve safety, efficiency, and sustainability. The findings are expected to contribute both theoretically and practically by providing a systematic framework that supports safer and greener chitosan production in medium-scale industries.

2. Method

2.1. Research Design

This study employed a quantitative–descriptive research design combined with a risk-based assessment approach to evaluate and improve the sustainability of chitosan production in a medium-scale industry. The methodologyintegrates process risk analysis, environmental performance assessment, and baseline production evaluation, aiming to support the development of a green production strategy. A similar applied and process-oriented approach has been successfully implemented in previous studies on chitosan production and industrial process analysis (Artiningsih, 2017) [1]; (Rauf, 2024) [25].

2.1. Study Object and System Boundary

The object of this research was a medium-scale chitosan production process utilizing shrimp shell waste as the primary raw material. The system boundary covered the main production stages, including:

1. Raw material preparation
2. Deproteinization
3. Demineralization
4. Deacetylation
5. Washing and drying

The analysis focused on process duration, chemical consumption, energy usage, water consumption, waste generation, and occupational safety risks within these stages. This system boundary approach is consistent with previous studies on chitosan processing and environmental assessment (Artiningsih, 2017) [1]; (Chou *et al*., 2020) [6].

2.2. Data Collection

Primary data were collected through direct observation, process measurement, and interviews with operators and supervisors. The collected data included:

- Quantity of raw materials and chemicals (NaOH and HCl)
- Processing time at each production stage
- Energy and water consumption
- Volume and characteristics of liquid waste
- Records of operational disturbances and safety incidents

Secondary data were obtained from production logs, standard operating procedures (SOPs), and relevant literature. The use of baseline operational data as a foundation for process evaluation follows the approach applied in previous chitosan production studies (Artiningsih, 2017) [1] and industrial waste analysis (Rauf, 2024) [25].

2.3. Environmental Performance Assessment

Environmental performance was evaluated using key performance indicators (KPIs), including:

- Chemical consumption per kg of raw material
- Energy consumption per kg of chitosan produced
- Water usage per kg of product
- Liquid waste generation per batch

This indicator-based assessment allows a practical evaluation of environmental efficiency without requiring a full Life Cycle Assessment (LCA), making it suitable for medium- scale industries with limited data availability (Chou *et al*., 2020) [6]; (Gupta *et al*., 2018) [9].

2.4. Risk Analysis Method

2.4.1. Hazard and Operability Study (HAZOP)

HAZOP was applied to systematically identify potential hazards and operational deviations at each production stage. Guide words such as *more*, *less*, *none*, and *reverse* were used to analyze deviations related to temperature, concentration, flow, and processing time. This method is widely used in chemical process industries to improve safety and reliability (Khan and Abbasi, 1998) [13]; (CCPS, 2008) [5]; (Stone *et al*., 2020) [28].

2.4.2. Failure Mode and Effect Analysis (FMEA)

FMEA was conducted to prioritize identified risks by calculating the Risk Priority Number (RPN), defined as the product of Severity (S), Occurrence (O), and Detection (D). The assessment scale ranged from 1 to 5 for each parameter. This approach enables the identification of critical process stages requiring immediate mitigation actions (Yang *et al*., 2019) [30]; (Lee *et al*., 2019) [19].

2.5. Data Analysis

Collected data were processed using descriptive statistical analysis to determine average values and performance ratios. Risk prioritization results from FMEA were integrated with environmental performance indicators to identify critical control points that influence both safety and sustainability. This integrated analysis approach aligns with green risk mitigation strategies previously proposed for chemical and manufacturing industries (Sari and Nugroho, 2020; Rauf, 2024) [25].

2.6. Research Output

The main outputs of this study include:

1. Baseline environmental and operational performance of chitosan production
2. Identification of critical risk points using HAZOP–FMEA integration
3. A risk-based green production strategy framework applicable to medium-scale industries

These outputs are intended to support practical decision-making and continuous improvement in sustainable chitosan manufacturing.

3. Results and Discussion

3.1. Baseline Production Performance of Chitosan

The baseline evaluation of the chitosan production process shows that one production batch processed 10 kg of shrimp shell waste, resulting in 2.6 kg of chitosan, equivalent to a yield of 26%. The total processing time reached approximately 16 hours per batch, dominated by deproteinization and deacetylation stages. This yield range is comparable to conventional chitosan production reported in previous studies, although it still reflects inefficiencies associated with chemical-intensive processing (Artiningsih, 2017) [1]; (Wang *et al*., 2021) [29].

Chemical consumption analysis indicates that the process required 0.75 kg of NaOH and 1.10 kg of HCl per batch, corresponding to 0.075 kg NaOH/kg raw material and 0.11 kg HCl/kg raw material. These values confirm the high dependency on alkaline and acidic reagents, which has been identified as a major environmental and safety concern in chitosan production systems (Kumar and Mehta, 2019) [16]; (Chou *et al*., 2020) [6].

Water consumption reached 160 L per batch, while liquid waste generation was approximately 80 L per batch, characterized by extreme pH conditions (<2 and >12). Such conditions require strict handling and treatment, particularly in medium-scale industries with limited wastewater treatment facilities. Similar challenges have been highlighted in small and medium chemical industries where resource efficiency and waste management remain critical issues (Islam *et al*., 2019) [12]; (Rauf, 2024) [25].

3.2. Environmental Performance Indicators

Environmental performance indicators were normalized per kilogram of chitosan produced to enable comparison with previous studies. The analysis shows that energy consumption reached 6.9 kWh/kg chitosan, while water consumption was 61.5 L/kg chitosan. These figures are higher than those reported for optimized or enzymatic chitosan production systems, indicating significant potential for efficiency improvement (Zhang *et al*., 2021) [31]; (Liu *et al*., 2020) [20].

The high consumption of chemicals and water reflects process inefficiencies typical of conventional chitosan production in medium-scale industries. Although the use of shrimp shell waste supports circular economy principles through resource recovery, the overall environmental performance remains suboptimal due to the linear use of chemicals and the lack of internal reuse mechanisms (Geissdoerfer *et al*., 2017) [8]; (Korhonen *et al*., 2018) [15].

These findings suggest that environmental improvement strategies should not only focus on alternative extraction methods but also consider operational risk mitigation and process control to reduce material losses and chemical overuse.

3.3. HAZOP Results: Identification of Critical Process Risks

The HAZOP analysis identified multiple deviations across the production stages, with the deproteinization and demineralization stages emerging as the most critical. Common deviations included excessive chemical concentration, prolonged reaction time, and inadequate temperature control. These deviations were associated with potential consequences such as violent reactions, chemical splashes, equipment corrosion, and operator exposure.

The presence of these hazards is consistent with findings in chemical process industries, where poor control of reaction parameters significantly increases safety risks (Khan and Abbasi, 1998) [13]; (Stone *et al*., 2020) [28]. In medium-scale industries, these risks are often exacerbated by manual operations and limited automation, as also observed in similar process analyses conducted by Rauf (2024) [25].

3.4. FMEA Results and Risk Prioritization

Based on the identified hazards, FMEA was conducted to prioritize risks using the Risk Priority Number (RPN). The deproteinization stage recorded the highest RPN value of 112, followed by the demineralization stage with an RPN of 96.

These high RPN values were primarily driven by high severity scores due to chemical exposure risks and moderate detection capability.

Lower RPN values were observed in the washing and drying stages, indicating relatively lower operational risks. The prioritization results highlight that risk mitigation efforts should focus on early-stage chemical treatments, where both safety and environmental impacts are most significant. Similar prioritization patterns have been reported in FMEA applications within chemical and pharmaceutical industries (Lee *et al*., 2019) [19]; (Yang *et al*., 2019) [30].

3.5. Integration of Risk Mitigation and Green Production Strategy

The integration of environmental performance indicators with HAZOP–FMEA results reveals a strong relationship between high-risk process stages and high resource consumption. Stages with elevated RPN values also exhibited excessive chemical usage, water demand, and waste generation. This finding supports the argument that risk mitigation and green production are interdependent objectives rather than separate goals.

From a macroergonomic and systems perspective, improving process control, operator training, and standard operating procedures can simultaneously reduce safety risks and environmental burdens (Hendrick, 2001) [10]; (Kleiner, 2006) [14]. In line with Total Quality Management principles, continuous improvement based on risk prioritization provides a structured pathway toward operational excellence in medium-scale chitosan industries (Oakland, 2014) [22].

Compared with studies focusing solely on chemical optimization (Kumar and Mehta, 2019) [16]; (Liu *et al*., 2020) [20], this study demonstrates that a risk-based green production strategy offers a more comprehensive framework by addressing safety, efficiency, and sustainability concurrently.

Table 1: Summary of Production Performance, Environmental Indicators, and Risk Assessment Results

No	Parameter	Unit	Value	Interpretation
A. Production Performance				
1	Raw material input	kg/batch	10.0	Shrimp shell waste processed per batch
2	Chitosan output	kg/batch	2.6	Final product yield
3	Production yield	%	26.0	Comparable with conventional processes
4	Total processing time	hours/batch	16.0	Dominated by chemical treatment stages
B. Chemical and Resource Consumption				
5	NaOH consumption	kg/batch	0.75	High alkaline usage
6	HCl consumption	kg/batch	1.10	Acid-intensive process
7	Water consumption	L/batch	160	High water demand
8	Liquid waste generation	L/batch	80	Extreme pH wastewater
C. Normalized Environmental Indicators				
9	Energy consumption	kWh/kg chitosan	6.9	Higher than optimized Processes
10	Water consumption	L/kg chitosan	61.5	Indicates low water efficiency
D. Risk Assessment Results (HAZOP–FMEA)				
11	Highest-risk process stage	–	Deproteinization	Chemical exposure risk
12	RPN (deproteinization)	–	112	High priority for mitigation
13	Second highest-risk stage	–	Demineralization	Process deviation risk
14	RPN (demineralization)	–	96	Moderate–high risk
15	Lowest-risk stage	–	Washing & drying	Relatively safe operation

3. Analyze and Discussion

4.1. Analyze

The summary results indicate that chitosan production in the observed medium-scale industry relies heavily on chemical-intensive processes. Although the utilization of shrimp shell waste aligns with circular economy principles, the yield of 26% and processing time of 16 hours per batch suggest operational inefficiencies. These findings are consistent with conventional chitosan extraction systems reported by Artiningsih (2017) [1] and Wang *et al*. (2021) [29].

Chemical usage intensity remains relatively high, particularly during deproteinization and demineralization stages. The NaOH and HCl consumption levels directly contribute to excessive liquid waste generation and extreme pH conditions, increasing both environmental burden and occupational safety risks. This pattern reflects common challenges in small- and medium-scale chemical industries with limited process control (Islam *et al*., 2019) [12]; (Rauf, 2024) [25]. Environmental performance indicators further confirm inefficiency, as energy and water consumption exceed those reported in optimized or green extraction studies (Liu *et al*., 2020) [20]; (Zhang *et al*., 2021) [31]. These results highlight the need for integrated improvement strategies beyond isolated chemical substitution.

4.2. Discussion

The integration of production performance, environmental indicators, and risk assessment reveals a strong correlation between high-risk stages and high resource consumption. Deproteinization, which recorded the highest RPN value (112), is also the stage with the greatest chemical usage and longest processing time. This confirms that risk-prone operations are simultaneously the least environmentally efficient, reinforcing the argument that safety and sustainability improvements should be addressed together. Previous studies on chitosan production have predominantly focused on optimizing chemical concentration or introducing alternative solvents to reduce environmental impact (Kumar and Mehta, 2019) [16]; (Liu *et al*., 2020) [20]. While effective, these approaches often overlook operational risk and human factors. By contrast, this study demonstrates that applying HAZOP–FMEA provides a structured basis for identifying priority stages where green production interventions will yield the greatest combined benefit.

From a macro ergonomic perspective, manual handling of hazardous chemicals, limited standardization, and low detection capability contribute to elevated risk levels (Hendrick, 2001) [10]; (Kleiner, 2006) [14].

Similar findings were reported in medium-scale industrial analyses by Rauf (2024) [25], emphasizing that process inefficiency and safety issues frequently originate from organizational and operational design rather than technology alone.

The findings also support Total Quality Management principles, where continuous improvement should target processes with the highest variability and risk (Oakland, 2014) [22]. Integrating risk prioritization into green production strategies enables industries to systematically reduce chemical usage, improve worker safety, and enhance environmental performance without requiring immediate high-cost technological changes.

Overall, this study extends existing literature by demonstrating that risk-based green production is a feasible and practical pathway for medium-scale chitosan industries, particularly in developing economies where resource and safety constraints coexist.

5. Conclusion

This study demonstrates that chitosan production in medium-scale industries, while supporting waste valorization, still faces substantial challenges related to chemical dependency, environmental efficiency, and process safety. The baseline assessment revealed a yield of 26%, accompanied by high water and energy consumption and the generation of chemically aggressive wastewater.

The integration of HAZOP and FMEA successfully identified deproteinization and demineralization as critical control stages, with Risk Priority Numbers exceeding acceptable thresholds. These stages were also responsible for the highest environmental burdens, confirming that risk mitigation and green production objectives are closely linked.

The findings highlight that a risk-based green production strategy offers a practical and systematic pathway for improving sustainability in medium-scale chitosan industries. Rather than relying solely on technological substitution, targeted risk mitigation at critical stages can reduce chemical usage, enhance occupational safety, and improve overall environmental performance. This approach provides a scalable foundation for transitioning toward safer and more sustainable chitosan production systems.

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