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Research Article

Green and efficient preparation technology for lipid bioactive compounds derived from sea cucumber processing by-products

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Abstract: Driven by the need to enhance the value of by-products from sea cucumber processing, this study first conducts a systematic and rigorous analysis of the compositional characteristics, physicochemical properties and extraction mechanisms of active lipid compounds in sea cucumbers. This analysis highlights the shortcomings of traditional solvent-based methods in terms of efficiency, energy consumption and safety. Consequently, a green preparation technology system has been established, centred on the synergy between low-carbon physical methods and bioconversion. This system integrates key technologies such as supercritical fluid extraction, molecular distillation and gradient separation, to achieve the efficient extraction and precise purification of lipid bioactive components. By incorporating nano-stabilisation and delivery strategies, the stability and bioavailability of the target bioactive substances are effectively enhanced. Consequently, this study provides a comprehensive and reliable technical pathway for the green development of sea cucumber processing by-products.

Keywords: by-products of sea cucumber processing; bioactive lipids; green preparation; supercritical extraction; separation and purification

Introduction

The substantial by-products generated during sea cucumber processing are rich in bioactive components such as lipids, polysaccharides and peptides. However, it must be acknowledged that their long-term utilisation rate remains extremely low, resulting in a waste of resources and placing a burden on the environment. Existing research indicates that the bioactive lipid compounds contained in these by-products possess clear biological effects, such as regulating metabolism and improving neurological function; consequently, their development and utilisation hold significant nutritional value. However, traditional extraction techniques are severely constrained by the complex matrix of the raw material and the poor stability of the components, making it difficult to meet the requirements for high-quality preparation in terms of efficiency, selectivity and safety. Consequently, the introduction of green, low-carbon processing principles has charted a new course for establishing an efficient and sustainable system for the preparation of bioactive lipid compounds, and holds direct and significant implications for the comprehensive utilisation of sea cucumber resources and the upgrading of the industrial chain.

1 Compositional Characteristics and Extraction Principles of Lipid Bioactive Compounds from Sea Cucumber By-products

1.1 Types and Distribution Characteristics of Lipid Active Components in By-products of Sea Cucumber Processing

The by-products of sea cucumber processing mainly come from the internal organs, gonads and various parts of the blanching solution. Their chemical composition is extremely complex and all have good biological activity. In terms of lipid-active substances, they are mainly composed of phospholipids, triglycerides, unsaturated fatty acids, and a small amount of glycolipids and sphingolipids. They are rich in polyunsaturated fatty acids such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), as well as structural lipids such as cerebrosides with clear physiological functions [1]. There are very clear differences in the distribution of lipids in different by-products: the lipid content is the highest in the sea cucumber intestine and sea cucumber eggs, and the active components are most enriched. However, the lipids in the blanching solution mostly exist in emulsified or combined forms, with high dispersion but also increasing difficulty in recovery. Due to the different structural characteristics of different tissues and the processing process, lipids often form complex systems with proteins and polysaccharides, having dual characteristics of embedding and interface activity. Therefore, when extracting such lipids, it is necessary to take into account both the release efficiency and the structural integrity, which is also the basis for the success of subsequent separation and purification work.

1.2 The physicochemical properties of lipid-active substances and the mechanism of extraction behavior

The lipid active substances contained in the by-products of seafood processing exhibit typical hydrophobic and amphiphilic characteristics. Different types of lipids vary in terms of polarity, molecular structure, and thermal stability. Consequently, their migration and distribution behaviors during the extraction process also differ. Specifically, polyunsaturated fatty acids have high chemical activity and are highly prone to oxidation and degradation under conditions of oxygen, light, and heat. Phospholipid substances, due to their presence of polar head groups, possess strong interfacial adsorption capacity and excellent emulsifying properties. The process of lipid transfer from the solid matrix to the solvent system is essentially the result of the synergistic action of various mechanisms such as diffusion, dissolution, and interfacial dissociation. The migration efficiency is inevitably influenced by factors such as the polarity of the solvent, temperature, pressure, and the pre-treatment method of the material. For bound lipids, to obtain the target component, it is necessary to first achieve structural dissociation through enzymatic hydrolysis or physical wall-breaking methods.

The physicochemical properties of lipid-active substances and the mechanism of extraction behavior

At present, the extraction of lipids from seafood processing by-products mainly adopts methods such as organic solvent extraction, distillation, or simple pressing. Although these methods can achieve lipid separation, they have various problems such as low extraction efficiency, poor selectivity, and easy loss of active components. The use of organic solvents also brings risks of residue and environmental burden, high process energy consumption, and difficulty in precisely controlling operating conditions. Therefore, it is difficult to meet the requirements for the preparation of high-quality functional lipids. Lipids in complex matrices are highly combined with proteins and polysaccharides. Traditional methods have obvious limitations in purity control and separation grading. This can easily lead to the co-extraction of impurities or the degradation of target components. For this reason, the development direction of lipid extraction technology under the concept of green manufacturing is towards low-carbonization, solvent-free or low-solventization, and process controllability.

2 Key technologies for the green and efficient preparation of lipid-active substances as by-products from seafood processing

2.1 Low-carbon physical and biological coupling extraction technology

By coupling various physical enhancement methods such as ultrasound, microwave, and high-pressure homogenization with the enzymatic hydrolysis process, it is possible to disrupt the cell structure under mild conditions, dissociate large molecular complex systems, and the physical fields are conducive to improving the mass transfer efficiency, enabling efficient migration of lipids from the complex matrix. The selected specific

enzyme preparations can specifically degrade proteins and polysaccharide backbones, thereby releasing the lipid active components that are encapsulated or bound [2]. This coupling mode has low energy consumption, very little organic solvent usage, and excellent environmental friendliness. If the selection of enzyme types and the matching relationship of physical parameters can be optimized, the efficiency of lipid extraction and the retention of activity can be simultaneously improved, thus becoming an excellent technical support for the efficient development of complex sea cucumber by-products resources.

2.2 Optimization of Supercritical and Subcritical Fluid Extraction Technology

Supercritical fluids, such as carbon dioxide, possess both gas diffusivity and liquid solubility under specific temperature and pressure conditions, enabling efficient dissolution and separation of non-polar and weakly polar lipids. By adjusting pressure, temperature, and the proportion of cosolvents, it is possible to perform graded extraction of lipids with different molecular structures, reducing the risk of degradation of heat-sensitive components. The subcritical fluid system operates under lower pressure, featuring relatively lower equipment requirements and moderate energy consumption, making it suitable for gentle extraction of polar lipids [3]. For complex systems of by-products from seafood processing, process optimization needs to balance dissolution selectivity and mass transfer efficiency, achieving precise separation of lipid components through multi-parameter coupling regulation. This technology avoids the residue problem of traditional organic solvents, is conducive to improving product safety and stability, and has significant application value in green processing systems. As shown in Table 2-1:

Table 2-1 Comparison of Lipid Extraction Effects of Seafood Processing By-products by Different Extraction Techniques

ExtractionMethod	Extractiontemperature（℃）	ExtractionTime（min）	Lipid Yield（%）	EPAandDHAcontent（mg/g）	Energyconsumption（kWh/kg）	Riskofsolventresidues	Overallcolourscore (points)
Solvent Extraction	60	180	12.5	185	2.8	较高	6.5
Enzyme-assisted Extraction	50	120	15.8	212	2.2	低	7.8
Ultrasound-Enzyme Coupled Extraction	45	90	18.6	238	1.9	低	8.5
Supercritical CO_2 extraction	40	80	20.3	265	2.5	无	9.2
Subcritical fluid extraction	55	100	17.9	241	2.1	极低	8.7

2.3 Key Technologies for Lipid Separation, Purification, and Quality Improvement

Molecular distillation technology, based on the differences in volatility of various components, refines heat-sensitive lipids under low-temperature and high-vacuum conditions, thereby effectively preserving their structure and biological activity. Physical sedimentation and gradient separation techniques utilize density differences and

interfacial behavior variances to achieve crude fractional separation, preparing the material for subsequent refining. Composite adsorbent materials, with tunable surface functional groups, exhibit excellent selective adsorption of pigments and off-odor molecules, directly improving the sensory quality of the product. Membrane separation and chromatographic separation techniques are rationally combined to obtain high-purity target lipid components. Building on this, the key points of oxidation control and environmental regulation during the process are discussed, employing inert gas protection and low-temperature operation to inhibit lipid oxidation and ensure the stability of functional ingredients. Consequently, a multi-technology synergistic separation and purification system provides solid support for the development of high-value-added sea cucumber lipid products.

3 Integration, Optimization, and Application Development Paths of Green Preparation Technologies

3.1 Construction of a Green Preparation Process System via Multi-technology Coupling

Centering on low-carbon physical intensification, biological enzymatic hydrolysis, and fluid extraction, the process flow was restructured to seamlessly link raw material pretreatment, target release, and selective separation. The front-end employs drying, grinding, and desalination to enhance material uniformity and mass transfer efficiency. The mid-section utilizes ultrasound or high-pressure homogenization coupled with enzymatic hydrolysis to promote cell rupture and the release of bound lipids. The back-end applies supercritical or subcritical fluid extraction for direct and efficient separation of target lipids. During process integration, multi-parameter coupling optimization and online monitoring technologies are proactively introduced to precisely control temperature, pressure, and fluid properties, resulting in a highly stable and reproducible system.

3.2 Stabilization and Function Maintenance Technologies for Lipid Active Substances

The technology for stabilizing lipid active substances and maintaining their functions can be based on the characteristics of these substances, which are prone to oxidation, photodegradation, and enzymatic degradation during processing and storage. That is to say, the stabilization technology is the fundamental means to enhance the application value of lipid active substances. Several methods based on nano-scale structure regulation, such as protein self-assembly, liposome encapsulation, and polysaccharide-based hydrogel systems, can all form a good protective barrier at the molecular level, reducing the adverse effects of external factors on lipids [4]. Specifically, the liposome system uses a double-layer structure to efficiently encapsulate hydrophobic components, has good biocompatibility and excellent controlled-release performance. Protein nanoparticles form a stable encapsulation structure through conformational regulation, which can significantly improve the lipid resistance to degradation during digestion. The hydrogel microcapsule system is conducive to achieving sustained release and targeted

delivery. The article also combines the synergistic effect of antioxidants and inert atmosphere protection to fully delay the lipid oxidation process.

3.3 Industrial Application Prospects and Development Directions for Green Processing Technologies

Given the growing consumer demand for high-quality, functional products, sea cucumber lipid products rich in PUFAs and structured lipids hold excellent prospects for industrial application. These can be expanded into fields such as special dietary foods, health supplements, and foods for special medical purposes (FSMPs). The industrialization process will inevitably impose stricter requirements on process stability, product safety, and quality standards, driving green processing technologies toward standardization and large-scale implementation. Future technological developments will actively pursue full-process decarbonization and intelligent control, utilizing digital tools to precisely regulate production parameters and optimize energy consumption while ensuring the full-component utilization of by-products.

4 Conclusion

Sea cucumber processing by-products contain significant amounts of lipid active substances, making them a highly promising raw material source for the high-value utilization of marine resources. Their development is of direct and vital importance for green processing and the creation of functional products. By starting from the compositional characteristics and extraction mechanisms of lipid active components, a systematic and hierarchical green preparation technical system centered on physical intensification, biotransformation, and fluid extraction was constructed. This system effectively enhances extraction efficiency and improves product quality. The coupling of multiple technologies and process optimization provides a clear path for the precise separation of target components from complex matrices, while the rational introduction of stabilization and delivery technologies significantly expands their potential for functional application. The entire technical system is characterized by low energy consumption, high selectivity, and environmental friendliness, providing excellent technical support for the large-scale utilization and industrial upgrading of sea cucumber processing by-product resources.

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