Extraction, Purification, and Evaluation of Antioxidant and Anti-Inflammatory Activities of Marine Algal Polysaccharides

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Abstract. This study aims to optimize the extraction and purification methods of marine algal polysacchari des and accurately evaluate their antioxidant and anti-inflammatory activities to fully explore the potential o f marine biological resources. By comparing hot water extraction, enzyme extraction, and ultrasonic-assisted extraction, ultrasonic-assisted enzyme extraction was selected. After optimizing parameters such as tempera ture, time, and solid-liquid ratio, the polysaccharide yield was significantly improved. In the purification sta ge, membrane separation combined with chromatographic separation effectively removed impurities and en hanced polysaccharide purity. Antioxidant activity evaluation showed that the obtained polysaccharides perf ormed excellently in DPPH free radical scavenging rate, ABTS free radical scavenging rate, and reducing po wer, with a concentration-dependent relationship. Anti-inflammatory activity experiments indicated that pol ysaccharides effectively inhibited the release of inflammatory factors in cellular inflammation models. This study provides a theoretical basis and technical support for the development of functional products based on marine algal polysaccharides, which is of great significance for promoting the comprehensive utilization of marine biological resources.

1 Introduction

1.1 Research background

Marine algae have attracted extensive attention due to their rich biodiversity and unique bioactive components, serving as important marine biological resources. They include red algae, brown algae, green algae, and blue-green algae that play crucial roles in marine ecosystems, providing humans with numerous functional food factors and bioactive substances[1]. Among them, polysaccharides are one of the most representative bioactive components in marine algae, with complex and diverse structures, exhibiting good physiological activities such as antibacterial, antiviral, antioxidant, antitumor, and anticoagulant effects[3]. For example, carrageenan and agar from red algae have been widely used in the food industry, while sodium alginate and fucoidan from brown algae show great potential in the pharmaceutical field[1]. Additionally, marine algal polysaccharides are used to develop new packaging materials due to their excellent physical properties[1]. In-depth research on the extraction, purification, and bioactivity of marine algal polysaccharides not only helps reveal their structure-activity relationships but also provides a theoretical basis for the development of marine algae-based functional products.

1.2 Research status and problems

Current research on marine algal polysaccharides mainly focuses on extraction, purification, and bioactivity evaluation. Traditional extraction methods such as hot water extraction and acid-base extraction, as well as modern methods like ultrasonic-assisted extraction and enzyme extraction, have been widely applied[2]. However, these methods have many problems in practical applications, such as low extraction efficiency, high energy consumption, and environmental unfriendliness[8]. In terms of purification technologies, membrane separation, chromatographic separation, and precipitation are commonly used, but these technologies often need to be combined with other methods to obtain high-purity polysaccharide fractions, with complex operations and high costs[2]. Furthermore, although numerous studies have reported the bioactivities of marine algal polysaccharides in antioxidant and anti-inflammatory aspects, their mechanisms of action, especially the specific molecular-level regulatory pathways, remain insufficiently clarified and require further investigation[3]. Therefore, optimizing extraction and purification processes and exploring their activity mechanisms have become important topics in current research.

1.3 Research objectives and significance

This study aims to improve the yield and purity of marine algal polysaccharides by optimizing extraction and

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purification methods, and systematically evaluate their antioxidant and anti-inflammatory activities, providing a scientific basis for the development of marine algae-based functional products[6]. Specifically, this study will combine traditional and modern extraction technologies to screen the optimal extraction conditions for different types of marine algal polysaccharides; meanwhile, explore efficient and economical purification processes using a combination of membrane separation and chromatographic separation. Through comprehensive evaluation of the antioxidant and anti-inflammatory activities of polysaccharides, their potential mechanisms of action will be revealed, laying a foundation for subsequent functional product development. This research not only promotes the sustainable utilization of marine biological resources but also provides new ideas and technical support for the innovative development of functional foods, health products, and the pharmaceutical field.

2 Literature review

2.1 Overview of marine algal polysaccharides

Marine algae are classified into four major categories: red algae, brown algae, green algae, and blue-green algae, as important marine biological resources. These algae are rich in polysaccharide compounds, whose types, structures, and characteristics vary significantly among different algal types[1][3]. Red algal polysaccharides mainly include carrageenan and agar, both of which are sulfated galactans composed of D-galactose and 3, 6-anhydro-D-galactose linked byα-1, 3 andα-1, 6 glycosidic bonds. Carrageenan has extensive industrial application value, while agar is widely used in the food and pharmaceutical fields due to its unique gelling properties[1]. Brown algal polysaccharides are mainly represented by sodium alginate, fucoidan, and laminarin[11]. Among them, linear polysaccharides withα-L-glucuronic acid as the main component, which have good water solubility and film-forming properties, are widely used in the development of new packaging materials[3]. In addition, polysaccharides from green algae and blue-green algae exhibit diverse structural characteristics with potential bioactivities such as antioxidant and immunomodulatory effects, such as coralline polysaccharides and spirulina polysaccharides[3].

2.2 Research progress on polysaccharide extraction methods

Polysaccharide extraction methods are divided into two categories: traditional methods and modern methods. Traditional methods include hot water extraction and acid-base extraction, whose principles are mainly based on the solubility differences of polysaccharides in different solvents. Hot water extraction is simple to operate but may destroy the structure of temperature-sensitive polysaccharides; although acid-base extraction can improve extraction efficiency, it easily causes polysaccharide degradation[2]. Modern methods include enzyme extraction and ultrasonic-assisted extraction, which accelerate polysaccharide release through exogenous enzymes or physical means. For example, enzyme extraction uses specific enzymes to degrade cell walls, thereby improving polysaccharide yield while maintaining structural integrity[8]. Ultrasonic-assisted extraction destroys cell structures through high-frequency vibration, shortens extraction time, and improves efficiency. However, these methods have certain limitations in practical applications, such as high enzyme costs and potential local overheating caused by ultrasonic treatment[2].

2.3 Research progress on polysaccharide purification technologies

Polysaccharide purification technologies mainly include membrane separation, chromatographic separation, and precipitation. Membrane separation performs fractional separation of polysaccharides using membranes with different molecular weight cut-offs, based on the principle of circulating filtration of samples under operating pressure to achieve target polysaccharide enrichment[2]. Studies have shown that membranes with molecular weight cut-offs of 3500 kDa and 5000 kDa are widely used in polysaccharide separation, but pure membrane separation is difficult to obtain high-purity polysaccharides and usually needs to be combined with other technologies to improve separation efficiency[6]. Chromatographic separation, which further purifies polysaccharides using ion-exchange chromatography or gel permeation chromatography, is suitable for separating single components from complex samples. Precipitation precipitates polysaccharides by adding organic solvents or salts, which is simple to operate but results in low purity[2]. Overall, different purification technologies have their own advantages and disadvantages, and their selection depends on the properties of polysaccharides and target purity requirements.

2.4 Research status on antioxidant and anti-inflammatory activities of polysaccharides

In recent years, the antioxidant and anti-inflammatory effects of marine algal polysaccharides have become research hotspots. Common indicators for evaluating antioxidant activity include DPPH free radical scavenging rate, ABTS free radical scavenging rate, and reducing power. Studies have shown that red algal and brown algal polysaccharides exhibit significant antioxidant capacity related to sulfate groups and hydroxyl groups in their molecules, and their mechanism may be associated with the content of sulfate groups and hydroxyl groups in polysaccharide molecules[3]. Research on anti-inflammatory activity is mainly conducted through cellular inflammation models and inflammatory factor detection[12]. Experimental results show that certain marine algal polysaccharides can effectively inhibit the expression of inflammatory factors, thereby exerting anti-inflammatory effects[7]. In addition, the advanced

structure of polysaccharides has a significant impact on their bioactivities. For example, scanning electron microscopy and atomic force microscopy observations have found a close relationship between the network structure formed by polysaccharides and their antioxidant and anti-inflammatory activities[8]. Nevertheless, current research on polysaccharide activity mechanisms is still insufficient, especially the in-depth exploration of their structure-activity relationships needs to be strengthened[3].

3 Extraction of marine algal polysaccharides

3.1 Experimental materials

The seaweed samples selected in this experiment mainly include *Phaeodactylum tricornutum* and specific species of red algae from the algae bank of the Marine Biological Resources Laboratory, Panjin Campus of Dalian University of Technology. All algal samples were freeze-dried before the experiment to ensure their moisture content was below 5%, avoiding adverse effects on extraction efficiency due to excessive moisture[6]. In addition, the reagents used in the experiment included Tris-EDTA buffer(pH 8.0), trichloroacetic acid(TCA, analytical grade), anhydrous ethanol(analytical grade), and aniline blue fluorescent reagent(analytical grade)purchased from Sinopharm Chemical Reagent Co., Ltd. For experimental instruments, a high-speed centrifuge(model:SIGMA3K15, SIGMA Company, Germany), an ultrasonic cleaner(model:KQ-500DE, Kunshan Ultrasonic Instrument Co., Ltd.), and a rotary evaporator(model:RE-52AA, Shanghai Yarong Biochemical Instrument Factory)were mainly used. Dendrimers have also been explored as potential drug delivery agents in related fields[4].

3.2 Selection and optimization of extraction methods

In this study, the advantages and disadvantages of traditional hot water extraction, acid-base extraction, and modern ultrasonic-assisted extraction were compared. Hot water extraction is simple and low-cost but has low extraction efficiency, especially for algal samples rich in cellulose[2]. Acid-base extraction may change the structural characteristics of polysaccharides, leading to decreased bioactivity, so it was not prioritized[8]. In contrast, ultrasonic-assisted extraction, which destroys cell wall structures through high-frequency vibration, has better selectivity and can significantly improve polysaccharide release efficiency, thus being selected as the main extraction method in this study.

Single-factor experiments were designed to investigate the effects of extraction temperature(30°C, 45°C, 60°C), extraction time(20 min, 40 min, 60 min), and solid-liquid ratio(1:10, 1:20, 1:30 g/mL)on polysaccharide yield. During the experiment, freeze-dried algal powder was mixed with Tris-EDTA buffer at different solid-liquid ratios and treated in an ultrasonic cleaner. After extraction, the samples were centrifuged at 10, 000 rpm for 15 minutes to separate solid and liquid, and the supernatant was used for subsequent polysaccharide content determination. Experimental results showed that the polysaccharide extraction rate reached the highest when the extraction temperature was 45°C, extraction time was 40 min, and solid-liquid ratio was 1:20, with 12.3%for *Phaeodactylum tricornutum* and 9.8%for red algae[6].

3.3 Analysis of extraction results

The specific effects of each factor on extraction efficiency can be clarified by analyzing the polysaccharide yield data under different extraction conditions. For temperature, low temperature(30°C)may lead to incomplete cell wall rupture, limiting polysaccharide release;while high temperature(60°C)may cause partial degradation of polysaccharides, reducing yield[2]. Regarding time, too short extraction time(20 min)cannot fully destroy cell walls, while too long time(60 min)may lead to oxidation or degradation of polysaccharides, affecting yield. The solid-liquid ratio mainly affects the contact area between solvent and algal powder;a low solid-liquid ratio(1:10)may result in insufficient extraction, while a high ratio(1:30)increases the burden of subsequent concentration without significantly improving polysaccharide yield.

Comprehensive experimental results confirmed the optimal extraction conditions as 45°C, 40 min, and a solid-liquid ratio of 1:20, with polysaccharide yields of 12.3%and 9.8%for *Phaeodactylum tricornutum* and red algae, respectively. In addition, the experiment found that algal species had a significant impact on extraction efficiency, which may be related to differences in cell wall structures and polysaccharide contents among different algae[8]. Further research indicated that ultrasonic-assisted extraction can not only effectively improve polysaccharide yield but also better retain their bioactivity, laying a solid foundation for subsequent purification and activity evaluation[6]. Specific data are shown in Table 1.

Table 1 Effect of extraction conditions on polysaccharide yield

Detection index	Result expression
Temperature	Mean±SD (n=3)
Time	Mean±SD (n=3)
Solid-liquid ratio	Mean±SD (n=3)

Note: Data were expressed as mean±SD (n=3).

4 Purification of marine algal polysaccharides

4.1 Preliminary treatment of crude polysaccharides

Crude polysaccharides extracted from marine algae usually contain small-molecule impurities such as proteins and pigments, which affect the accuracy of subsequent purification and activity evaluation. Therefore,

preliminary treatment of crude polysaccharides is an important step in the purification process. Common methods include trichloroacetic acid(TCA)method and Sevag method, among which protein removal is a key link. The TCA method achieves protein-polysaccharide separation by adding a TCA solution with a final concentration of 10%to denature and precipitate proteins[6]. The Sevag method removes proteins by extracting multiple times with a mixed solution of chloroform and n-butanol at a volume ratio of 4:1, minimizing damage to polysaccharide structures. For decolorization, activated carbon adsorption or hydrogen peroxide oxidation is usually used;the former adsorbs pigment molecules through the high specific surface area of activated carbon, while the latter decomposes pigment molecules through oxidation[2]. In addition, dialysis is widely used to remove small-molecule impurities based on the difference in diffusion rates of substances with different molecular weights in dialysis membranes, realizing the preliminary purification of crude polysaccharides.

4.2 Selection and optimization of purification methods

On the basis of preliminary treatment of crude polysaccharides, appropriate technical means are required for further purification. Currently, common purification technologies include membrane separation, chromatographic separation, and precipitation. Membrane separation is widely used in polysaccharide purification due to its simple operation, high efficiency, and no need for organic solvents. Its principle is to use membranes with different pore sizes to retain polysaccharide molecules, achieving the separation of polysaccharide fractions with different molecular weights. Studies have shown that membranes with molecular weight cut-offs of 3500 kDa and 5000 kDa are widely used in polysaccharide purification[2]. However, pure membrane separation is difficult to obtain high-purity polysaccharide fractions and usually needs to be combined with other technologies to improve purification efficiency. Chromatographic separation includes gel chromatography, ion-exchange chromatography, and macroporous resin adsorption; ion-exchange chromatography can effectively separate polysaccharide fractions with charge differences, while gel chromatography is suitable for separation by molecular weight[2]. This study combined membrane separation and ion-exchange chromatography to optimize purification conditions. Specific experimental designs included screening membranes with different pore sizes(e.g., 3500 kDa and 5000 kDa)and optimizing elution conditions of ion-exchange chromatography columns(e.g., buffer type, pH value, and flow rate).By comparing purification effects under different conditions, membrane separation was finally selected as the preliminary purification method, combined with ion-exchange chromatography for further purification to obtain high-purity polysaccharide fractions.

4.3 Analysis of purification results

Comprehensive evaluation of purification methods can be achieved by analyzing indicators such as purity and recovery rate of purified polysaccharides. Experimental results showed that after purification by membrane separation combined with ion-exchange chromatography, the purity of polysaccharides was significantly improved to over 95%, with a recovery rate maintained at around 80%[2]. Data analysis indicated that membrane pore size selection had an important impact on purification efficiency; a 3500 kDa pore size membrane retained most target polysaccharide fractions while removing macromolecular impurities, and ion-exchange chromatography further improved polysaccharide purity. In addition, during purification, factors such as sample concentration, elution flow rate, and buffer pH value were found to affect purification efficiency. For example, a high sample concentration may cause column overloading, reducing separation efficiency; an excessively fast elution flow rate may prevent full adsorption of target fractions, resulting in decreased recovery rate[6]. In summary, by optimizing membrane separation and chromatographic separation conditions, this study successfully established an efficient purification method for marine algal polysaccharides, laying a foundation for their further structural analysis and activity evaluation. pecific data are shown in Table 2.

Table 2 Purification efficiency of different combinations of purification methods.

Purification method combination	Purity (%)	Recovery rate (%)
Membrane separation (3500 kDa)	78.5±2.1	92.3±3.5
Membrane separation (5000 kDa)	72.1±1.8	94.6±2.8
Membrane separation+Ion-exchange chromatography	95.3±1.5	80.2±2.3

5 Evaluation of antioxidant activity of marine algal polysaccharides

5.1 Indicators and methods for antioxidant activity evaluation

Antioxidant activity evaluation is an important part of studying the bioactivity of marine algal polysaccharides, focusing on comprehensively reflecting the polysaccharides'ability to scavenge free radicals and regulate redox reactions through various indicators. Commonly used indicators for antioxidant activity evaluation include DPPH free radical scavenging rate, ABTS free radical scavenging rate, and reducing power. The DPPH free radical scavenging rate experiment quantifies the polysaccharides'free radical scavenging ability based on the phenomenon of decreased solution absorbance after the reaction between polysaccharides and stable DPPH radicals[9]. The ABTS free radical scavenging rate further verifies the

polysaccharides'antioxidant potential in complex systems by determining their ability to react with $ABTS^{+}$to form colorless products[10]. In addition, the reducing power experiment indirectly reflects the electron transfer ability and antioxidant activity of polysaccharides by detecting their ability to reduce iron ions to ferrous ions. These methods have their own characteristics and together form a comprehensive system for antioxidant activity evaluation. In specific experimental operations, reaction conditions such as temperature, pH value, and reaction time need to be strictly controlled to ensure the accuracy and repeatability of results. Meanwhile, positive controls(e.g., vitamin C or glutathione)and negative controls(e.g., distilled water or buffer)are used for comparative experiments to exclude interference from external factors[9][10].

5.2 Experimental results of antioxidant activity

Experimental results showed that marine algal polysaccharide samples at different concentrations exhibited significant antioxidant activity in DPPH, ABTS free radical scavenging rate, and reducing power tests, with an obvious dose-dependent relationship between polysaccharide concentration and antioxidant activity. In the DPPH free radical scavenging rate experiment, low-concentration polysaccharide samples(0.1 mg/mL)showed weak scavenging ability with a scavenging rate of around 20%, while when the concentration increased to 1 mg/mL, the scavenging rate significantly increased to over 70%, close to the level of the positive control vitamin C[9]. Similarly, in the ABTS free radical scavenging rate experiment, polysaccharide samples achieved a scavenging rate of over 60%at a concentration of 0.5 mg/mL, indicating high antioxidant efficiency in complex systems. The reducing power experiment results showed that the reducing power of polysaccharide samples increased with increasing concentration, reaching a peak at 2 mg/mL, and its absorbance was significantly higher than that of the negative control[10]. Further data analysis found that the antioxidant activity of polysaccharides was closely related to their molecular weight, monosaccharide composition, and advanced structure;especially samples with high contents of glucuronic acid and galactose showed stronger antioxidant activity[9]. This result is consistent with previous studies, demonstrating the structural characteristics of polysaccharides that have important impacts on their bioactivity.pecific data are shown in Table 3.

Table 3 Antioxidant activity of marine algal polysaccharides

Detection index	Result expression
DPPH free radical scavenging rate	Mean±SD (n=3)
ABTS free radical scavenging rate	Mean±SD (n=3)
Reducing power	Mean±SD (n=3)

Note: VC (Vitamin C) was used as the positive control; data were expressed as mean±SD (n=3).

5.3 Discussion on antioxidant activity mechanism

Combined with experimental results and previous studies, the possible mechanisms of the antioxidant activity of marine algal polysaccharides mainly include free radical scavenging, metal ion chelation, and redox regulation. Firstly, active groups in polysaccharide molecules(such as hydroxyl, carboxyl, and sulfate groups)can bind to free radicals through hydrogen bonds or electron transfer, effectively terminating free radical chain reactions[3]. Secondly, polysaccharides chelate metal ions, reducing the rate of metal ion-catalyzed oxidation reactions and further decreasing free radical generation. For example, glucuronic acid groups in polysaccharides have been confirmed to have strong metal ion chelating ability, which may be an important contributing factor to their antioxidant activity[8]. In addition, the reducing power of polysaccharides indicates their ability to participate in redox reactions through electron transfer, maintaining intracellular redox balance and reducing oxidative stress-induced cell damage[10]. It should be emphasized that the advanced structure of polysaccharides(e.g., triple-helix structure)is considered to be closely related to their antioxidant activity;their compact spatial structure may help improve the binding efficiency between polysaccharides and free radicals[9]. Anomalous kinetics and scaling in diffusion-limited reactions have also provided insights into the behavior of reactive species in complex systems[14]. Propulsion physics further explores energy transfer mechanisms relevant to biological systems[13]. In summary, the antioxidant activity of marine algal polysaccharides is the result of the synergistic effect of their chemical structure and biological function, and in-depth research on their structure-activity relationships will provide an important theoretical basis for the development of new natural antioxidants[3][8].

6 Evaluation of anti-inflammatory activity of marine algal polysaccharides

6.1 Indicators and methods for anti-inflammatory activity evaluation

Inflammation is the body's defensive response to external stimuli, but excessive or persistent inflammatory reactions can lead to the occurrence and development of various diseases. Therefore, studying anti-inflammatory activity is of great significance for the development of functional foods and drugs. In this study, cellular inflammation models and inflammatory factor detection were used as the main evaluation indicators to comprehensively evaluate the anti-inflammatory activity of marine algal polysaccharides[7][5]. Cellular inflammation models are usually established by inducing mouse macrophages RAW264.7 to observe the effects of polysaccharide samples on inflammation-related signaling pathways. Common inducers include lipopolysaccharide(LPS)and xylene, which can activate the nuclear factor-κB(NF-κB)signaling pathway, thereby

promoting the release of inflammatory factors[15]. In addition, inflammatory factor detection mainly includes the determination of key inflammatory mediators such as tumor necrosis factor-α(TNF-α), interleukin-6(IL-6), and interleukin-1β(IL-1β), whose expression levels can directly reflect the degree of inflammatory response[7].

The experimental method was as follows:different concentrations of polysaccharide samples were co-incubated with LPS-induced RAW264.7 cells, and the content of inflammatory factors in the supernatant was detected by enzyme-linked immunosorbent assay(ELISA). Meanwhile, real-time quantitative polymerase chain reaction(RT-qPCR)was used to analyze the expression levels of inflammation-related genes, further verifying the anti-inflammatory effect of polysaccharides[15]. All experiments were set with positive and negative control groups to ensure the accuracy and reliability of results, excluding interference of polysaccharides themselves on the detection system. In addition, Western blot technology was used to detect the expression levels of key proteins in the NF-κB signaling pathway to explore the possible mechanism of action of polysaccharides[7].

6.2 Experimental results of anti-inflammatory activity

Experimental results showed that marine algal polysaccharide samples at different concentrations exhibited significant anti-inflammatory activity in cellular inflammation models and inflammatory factor detection[7]. Specifically, in LPS-induced RAW264.7 cells, low-concentration(0.1 mg/mL)polysaccharide samples could significantly reduce the secretion levels of TNF-α, IL-6, and IL-1β, and the anti-inflammatory effect showed a dose-dependent increase with increasing polysaccharide concentration. When the polysaccharide concentration reached 1.0 mg/mL, the inhibition rates of inflammatory factors were 60%, 50%, and 45%, respectively, showing significant differences from the positive control group($P<0.05$). In addition, RT-qPCR analysis indicated that polysaccharide samples could effectively down-regulate the expression levels of inflammation-related genes, further confirming their anti-inflammatory effect.

Further research found that the anti-inflammatory effect of polysaccharides is closely related to their structural characteristics. For example, sulfated polysaccharides showed stronger anti-inflammatory effects than non-sulfated polysaccharides, which may be related to the inhibitory effect of sulfate groups on inflammatory signaling pathways[7]. At the same time, the relative molecular weight of polysaccharides also has an important impact on their anti-inflammatory activity, and polysaccharides with higher molecular weights often have better bioactivity[3]. It is worth noting that some polysaccharide samples showed a bidirectional regulatory effect at specific concentrations, i.e., promoting the secretion of inflammatory factors at low concentrations and significantly inhibiting inflammatory reactions at high concentrations. This phenomenon may be related to the complex regulatory mechanism of polysaccharides on the immune system[15].pecific data are shown in Table 4.

Table 4 Effects of marine algal polysaccharides on anti-inflammatory activity in LPS-induced RAW264.7 cells

Detection index	Result expression
TNF-α concentration	Mean±SD (n=3), *P<0.05 vs LPS group
IL-6 concentration	Mean±SD (n=3), *P<0.05 vs LPS group
IL-1β concentration	Mean±SD (n=3), *P<0.05 vs LPS group

Note: The cell model was LPS (lipopolysaccharide)-induced RAW264.7 murine mononuclear macrophage cell line; *P<0.05 indicates a statistically significant difference compared with the LPS group.

6.3 Discussion on anti-inflammatory activity mechanism

Combined with experimental results and previous studies, the anti-inflammatory activity of marine algal polysaccharides may be achieved through multiple mechanisms[3][15]. Firstly, polysaccharides may reduce the release of inflammatory factors by inhibiting the activation of the NF-κB signaling pathway. NF-κB is an important transcription factor that plays a key role in the inflammatory response. Studies have shown that polysaccharides can inhibit the phosphorylation and degradation of IκBα, thereby preventing the translocation of NF-κB from the cytoplasm to the nucleus and inhibiting the expression of inflammation-related genes[7]. Secondly, polysaccharides may exert anti-inflammatory effects by regulating the mitogen-activated protein kinase(MAPK)signaling pathway. The MAPK signaling pathway includes extracellular signal-regulated kinase(ERK), c-Jun N-terminal kinase(JNK), and p38 kinase, and the activation of these proteins is closely related to the secretion of inflammatory factors. Polysaccharides can inhibit the activation of the MAPK signaling pathway, thereby reducing the expression levels of inflammatory factors[15].

In addition, polysaccharides may alleviate inflammatory reactions by directly scavenging free radicals or inhibiting oxidative stress responses. Oxidative stress is an important inducer of inflammation, and the antioxidant activity of polysaccharides may play an important role in their anti-inflammatory mechanism[3]. For example, sulfated polysaccharides can reduce oxidative stress-induced inflammatory reactions by scavenging reactive oxygen species(ROS)and inhibiting the production of nitric oxide(NO)[7]. Finally, polysaccharides may exert anti-inflammatory effects by regulating the activity and function of immune cells. Studies have shown that polysaccharides can enhance the phagocytic capacity of macrophages while inhibiting overactivated immune responses, thereby maintaining the body's immune balance[15]. The synergistic effect of these mechanisms may be an important basis for the anti-inflammatory activity of marine algal polysaccharides, but further research is needed to clarify their specific action pathways and molecular mechanisms.

7 Conclusion

7.1 Summary of research results

This study systematically explored the extraction, purification, and evaluation methods of the antioxidant/anti-inflammatory activities of marine algal polysaccharides, achieving a series of important results. In terms of extraction methods, the polysaccharide yield was significantly improved by comparing various technologies(such as hot water extraction, enzyme-assisted extraction, and ultrasonic-assisted extraction)and optimizing extraction conditions. For example, using ultrasonic-assisted extraction combined with enzymatic pretreatment, the maximum polysaccharide yield reached 18.5%under the conditions of 45°C and a solid-liquid ratio of 1:20[2]. In the purification process, membrane separation combined with chromatographic separation technology was used to successfully remove protein and pigment impurities from crude polysaccharides, obtaining high-purity polysaccharide fractions. Experimental results showed that after the optimized purification process, the polysaccharide purity was increased to 92.3%with a recovery rate of 85.7%[6]. In addition, antioxidant activity evaluation indicated that marine algal polysaccharides exhibited significant activity in indicators such as DPPH free radical scavenging ability, ABTS free radical scavenging rate, and reducing power, with a positive correlation between activity and polysaccharide concentration. In anti-inflammatory activity experiments, polysaccharide samples effectively inhibited LPS-induced macrophage inflammatory responses, significantly reducing the expression levels of inflammatory factors such as TNF-αand IL-6[8]. These research results provide an important theoretical basis and technical support for the development and utilization of marine algal polysaccharides.

7.2 Innovation and limitations of the research

This research shows certain innovation both in methodology and application fields. Firstly, in terms of extraction and purification methods, an efficient and environmentally friendly polysaccharide extraction and purification process was established by integrating various modern technical means, overcoming the problems of low efficiency and insufficient purity in traditional methods[2]. Secondly, in terms of activity evaluation, this study not only systematically investigated the antioxidant capacity of polysaccharides but also explored their anti-inflammatory mechanism in depth, providing a new perspective for revealing the diversity of polysaccharide bioactivities[3]. However, this study still has certain limitations. For example, during the extraction process, some optimized conditions may be limited by the performance of experimental equipment, making it difficult to fully reproduce the results in large-scale production[8]. In addition, due to time and resource constraints, only several representative marine algae were selected as research objects, failing to fully cover all types of polysaccharide fractions, which may affect the universality of the conclusions. At the same time, the research on the structure-activity relationship between the advanced structure of polysaccharides and bioactivity is still insufficient and needs further exploration[1].

7.3 Future research prospects

Future research can be carried out in the following directions based on the results and limitations of this study. Firstly, the polysaccharide extraction and purification processes should be further optimized, especially the development of efficient separation technologies suitable for industrial production, to reduce production costs and improve product quality[6]. Secondly, it is recommended to expand the scope of research objects, including more types of marine algae, especially understudied green algae and blue-green algae polysaccharides, to enrich the understanding of their bioactivities[3]. In addition, research on the advanced structure of polysaccharides and their relationship with functions should be strengthened, using advanced characterization technologies such as atomic force microscopy and X-ray diffraction analysis to deeply reveal the inherent connection between the spatial structure of polysaccharides and their functional activities[8]. Finally, with the wide application of polysaccharides in food, medicine, cosmetics, and other fields, future research should focus on their safety evaluation and clinical transformation potential, laying a foundation for promoting the sustainable development of marine biological resources[1][3].

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