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Heavy Sustainable Cultivation and Environmental Impact of *Laminaria japonica* Farming

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Abstract The primary goal of this study is to evaluate the sustainable cultivation practices and environmental impacts associated with the farming of *Laminaria japonica*, a widely cultivated brown alga known for its economic and ecological significance. The study found that *Laminaria japonica* exhibits high adaptability to various environmental conditions, which supports its extensive cultivation in different regions, including subtropical areas. The alga's high carbohydrate content and polysaccharides, such as laminarin and alginate, contribute to its potential as a biofuel feedstock, with significant hydrogen production yields. Additionally, different extraction methods of *L. japonica* polysaccharides showed varying structural features and antioxidant activities, suggesting potential applications in food and pharmaceutical industries. The environmental impact assessment revealed that biochar derived from *L. japonica* contains environmentally persistent free radicals, which vary depending on the habitat and pyrolysis conditions. Furthermore, the degradation of algin content in *L. japonica* feedstuff improved the growth performance and disease resistance of sea cucumbers, indicating its potential as an alternative feed source. The findings suggest that *Laminaria japonica* farming is not only sustainable but also offers significant environmental and economic benefits. Its adaptability to different climates, high biofuel potential, and diverse applications in various industries underscore its importance. However, the environmental implications, such as the formation of persistent free radicals in biochar, warrant further investigation to optimize cultivation practices and minimize negative impacts.
Keywords *Laminaria japonica*; Sustainable cultivation; Environmental impact; Biofuel; Polysaccharides; Biochar; Sea cucumber feed; Antioxidant activities

1 Introduction

Laminaria japonica, commonly known as kelp, is a type of brown seaweed extensively cultivated in various parts of the world, particularly in East Asia. This seaweed is not only a significant source of food but also holds substantial economic and environmental importance. The cultivation of *Laminaria japonica* has been expanding due to its numerous benefits, including its nutritional value and its potential role in environmental sustainability.

Laminaria japonica farming has a long history, especially in countries like Japan, China, and Korea, where it is a staple in the diet and a key component of traditional medicine. The farming techniques have evolved over the years, allowing for large-scale production and consistent quality. The seaweed is rich in dietary fibers, vitamins, and minerals, making it a valuable addition to the human diet (Aoe et al., 2021; Kim et al., 2018). Additionally, it has been shown to have various health benefits, such as reducing body fat and improving lipid profiles (Aoe et al., 2021; Kim et al., 2018).

The sustainable cultivation of *Laminaria japonica* is crucial for several reasons. Firstly, it helps in maintaining the ecological balance by improving water quality and regulating phytoplankton communities in eutrophic waters (Jiang et al., 2020). Kelp farming can also mitigate the effects of coastal eutrophication and harmful algal blooms, which are significant environmental concerns (Jiang et al., 2020). Moreover, sustainable practices ensure that the seaweed's beneficial properties, such as its prebiotic effects and potential in reducing obesity, are preserved for future generations (Kim et al., 2018; Zhang et al., 2020). The environmental benefits extend to carbon sequestration and providing habitats for marine life, further emphasizing the need for sustainable farming practices (Swanson and Fox, 2007). This study aims to evaluate the current farming techniques and their effectiveness in different environmental conditions, investigate the ecological benefits of *Laminaria japonica* cultivation, particularly in terms of water quality improvement and biodiversity enhancement, assess the potential health benefits of *Laminaria japonica*, focusing on its nutritional value and bioactive compounds, and develop guidelines for sustainable farming practices that can be adopted globally to maximize both economic and environmental benefits.

By achieving these objectives, this research hopes to contribute to the broader understanding of sustainable aquaculture and its role in environmental conservation and human health.

2 Cultivation Practices of *Laminaria japonica*

2.1 Traditional farming methods

Traditional farming methods of *Laminaria japonica*, a large marine brown alga, have been practiced for centuries, particularly in East Asia. These methods typically involve the collection of wild spores, which are then cultivated on ropes or nets suspended in the ocean. The ropes are anchored to the seabed and buoyed to maintain optimal light exposure and water flow. This method relies heavily on natural environmental conditions, such as water temperature, salinity, and nutrient availability, to ensure the growth and development of the algae. Traditional methods are labor-intensive and can be less predictable due to their dependence on natural conditions (Huang et al., 2020; Marín et al., 2019).

2.2 Modern techniques and innovations

Modern techniques in the cultivation of *Laminaria japonica* have introduced significant innovations aimed at increasing yield and sustainability. One such technique is the use of controlled hatcheries for spore production, which allows for the selection of high-quality spores and more consistent cultivation outcomes. Additionally, advancements in aquaculture technology, such as the use of automated systems for monitoring and adjusting environmental parameters, have improved the efficiency and scalability of *Laminaria japonica* farming. Innovations in biochar production from *Laminaria japonica* have also been explored, highlighting the potential for sustainable energy production and environmental benefits (Brigljević et al., 2019; Huang et al., 2020). Furthermore, the integration of *Laminaria japonica* farming with other aquaculture practices, such as the cultivation of shellfish, has been shown to enhance water quality and promote a more balanced ecosystem (Jiang et al., 2020).

2.3 Growth and harvesting cycles

The growth and harvesting cycles of *Laminaria japonica* are influenced by various environmental factors and cultivation practices. Typically, the growth cycle begins with the seeding of spores onto cultivation ropes or nets, which are then deployed in the ocean. The algae undergo a rapid growth phase, particularly during the spring and summer months when water temperatures and nutrient levels are optimal. Harvesting usually occurs in late summer to early autumn, when the algae have reached their maximum biomass. The timing of the harvest is crucial to ensure the highest quality and yield of the product. Studies have shown that the growth environment, including factors such as water temperature and nutrient availability, can significantly impact the growth rate and biomass of *Laminaria japonica* (Huang et al., 2020; Jiang et al., 2020; Wang et al., 2022). Additionally, the use of modern techniques, such as controlled hatcheries and automated monitoring systems, can help optimize the growth and harvesting cycles, leading to more efficient and sustainable production (Brigljević et al., 2019; Marín et al., 2019).

3 Economic Importance of *Laminaria japonica*

3.1 Market demand and supply

Laminaria japonica, commonly known as kelp, is a significant product in the global aquaculture market, particularly in China, which is the largest provider of aquaculture products. The demand for *Laminaria japonica* is driven by its various applications, including food, pharmaceuticals, and biochar production. The production of *Laminaria japonica* in China is substantial, with the city of Ningde being a notable case study. The life cycle assessment of *Laminaria japonica* production in Ningde indicates a mean exergy demand value of 0.25 GJ eq. per live-weight ton, highlighting its relatively low resource use compared to other mariculture products (Marín et al., 2019). This efficient resource use contributes to the high market supply and meets the growing demand for sustainable aquaculture products.

3.2 Economic benefits for local communities

The cultivation of *Laminaria japonica* provides significant economic benefits to local communities involved in its farming. The mariculture sector, including *Laminaria japonica* farming, supports the livelihoods of many local populations by providing employment opportunities and contributing to the local economy. The efficient resource management and sustainable practices in *Laminaria japonica* farming can further enhance these economic benefits. Policies aimed at improving farm design, input management, and spatial planning of marine areas can lead to increased resource efficiency and reduced environmental impacts, thereby supporting the long-term economic sustainability of local communities (Marín et al., 2019).

3.3 Industry trends and developments

The *Laminaria japonica* industry is witnessing several trends and developments aimed at enhancing sustainability and economic viability. One notable development is the use of *Laminaria japonica* as a biomass feedstock for biochar production. Research has shown that biochars derived from *Laminaria japonica* grown in different habitats exhibit varying levels of environmentally persistent free radicals (EPFRs), which are influenced by the growth environment and pyrolysis temperatures (Huang et al., 2020). This indicates the potential for *Laminaria japonica* to contribute to sustainable biochar production, which can be used in soil improvement and carbon sequestration. Additionally, the focus on efficient resource management and sustainable practices in *Laminaria japonica* farming is expected to drive further industry advancements and support the growing market demand for eco-friendly aquaculture products (Marín et al., 2019; Huang et al., 2020).

4 Environmental Impact of *Laminaria japonica* Farming

4.1 Impact on marine ecosystems

Laminaria japonica farming has significant implications for marine ecosystems. The large-scale cultivation of this brown alga can alter local marine environments, primarily through changes in habitat structure and nutrient dynamics. For instance, the introduction of extensive *Laminaria japonica* farms can provide new habitats for various marine organisms, potentially increasing local biodiversity. However, it can also lead to habitat displacement for species that previously occupied the area (Marín et al., 2019). Additionally, the farming practices can influence the formation of environmentally persistent free radicals (EPFRs) in biochars derived from *Laminaria japonica*, which vary depending on the growth environment of the algae (Huang et al., 2020). These EPFRs can have long-term environmental impacts, although their specific effects on marine ecosystems require further study.

4.2 Water quality and nutrient cycling

The cultivation of *Laminaria japonica* can significantly affect water quality and nutrient cycling in marine environments. The algae can absorb and sequester nutrients from the water, potentially mitigating eutrophication in nutrient-rich coastal areas. However, the farming process itself can introduce nutrients and organic matter into the water, which may lead to localized eutrophication if not managed properly (Chu et al., 2019). Moreover, the decomposition of *Laminaria japonica* biomass can release nutrients back into the water, influencing nutrient cycling and potentially leading to shifts in the composition of local microbial communities (Duan et al., 2019). These changes can have cascading effects on water quality and the overall health of marine ecosystems.

4.3 Biodiversity and habitat changes

Laminaria japonica farming can lead to significant changes in local biodiversity and habitat structures. The physical presence of the algae farms can create new habitats for marine organisms, potentially increasing local biodiversity by providing shelter and food sources (Marín et al., 2019). However, this can also result in the displacement of native species and changes in the composition of local communities. For example, the introduction of *Laminaria japonica* can alter the abundance and diversity of benthic organisms, which can have broader ecological implications (Duan et al., 2019). Additionally, the farming practices can impact the gut microbiota of local marine species, influencing their health and metabolic processes (Chu et al., 2019). These biodiversity and habitat changes highlight the need for careful management and monitoring of *Laminaria japonica* farming to ensure sustainable practices that minimize negative environmental impacts.

5 Sustainability Practices in *Laminaria japonica* Farming

5.1 Eco-friendly farming techniques

Eco-friendly farming techniques are essential for the sustainable cultivation of *Laminaria japonica*. One effective method is the use of organic farming practices, which have been shown to benefit multiple wildlife taxa and enhance biodiversity. For instance, organic farming in rice paddies has been associated with higher species richness and abundance of various taxonomic groups, including plants, invertebrates, and birds (Katayama et al., 2019). Applying similar organic practices to *Laminaria japonica* farming could potentially yield similar ecological benefits. Additionally, the use of natural fertilizers and the avoidance of chemical pesticides can help maintain the health of marine ecosystems and reduce the environmental footprint of seaweed farming.

5.2 Waste management and recycling

Effective waste management and recycling are crucial for minimizing the environmental impact of *Laminaria japonica* farming. One innovative approach is the conversion of seaweed biomass into biochar, which can be used as a soil amendment to improve soil health and sequester carbon. Research has shown that biochars derived from *Laminaria japonica* exhibit environmentally persistent free radicals (EPFRs), which can vary depending on the pyrolysis temperature and the habitat of the seaweed (Huang et al., 2020). Additionally, the byproducts of *Laminaria japonica*, such as soluble dietary fiber (SDF), can be utilized in various applications, including functional foods and supplements, thereby reducing waste and promoting a circular economy (Wang et al., 2022) (Figure 1).

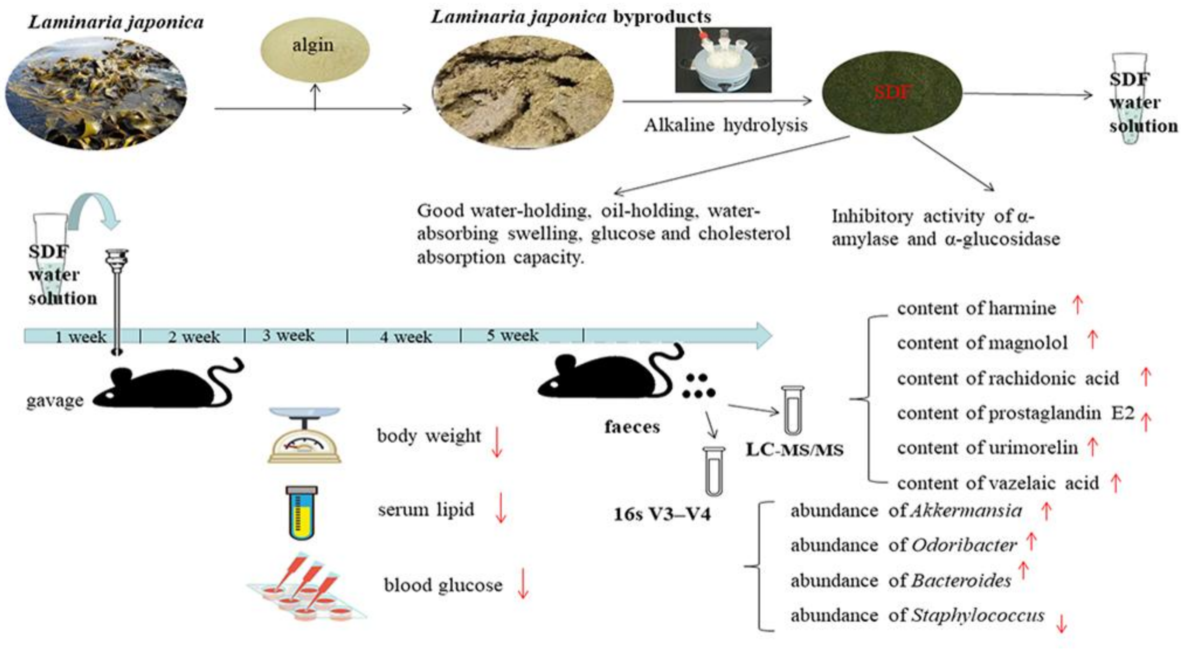

Figure 1 Impact of soluble dietary fiber (SDF) from *Laminaria japonica* on diabetic mice (Adapted from Wang et al., 2022)

Wang et al. (2022) depicts the process and benefits of using soluble dietary fiber (SDF) derived from *Laminaria japonica* byproducts in diabetic mice. SDF, known for its excellent water-holding, oil-holding, and glucose absorption capacities, was administered to diabetic mice. The treatment resulted in reduced body weight, lower serum lipid levels, and decreased blood glucose. Additionally, SDF altered the gut microbiota, increasing beneficial bacteria like *Akkermansia*, *Odoribacter*, and *Bacteroides*, while reducing harmful *Staphylococcus*.

Metabolomic analysis revealed elevated levels of bioactive compounds, such as harmine and prostaglandin E2. These findings suggest that SDF from *Laminaria japonica* can alleviate type 2 diabetes symptoms, highlighting its potential as a functional food ingredient for managing diabetes.

5.3 Sustainable resource use

Sustainable resource use involves optimizing the utilization of *Laminaria japonica* to maximize its economic and environmental benefits. For example, the co-production of biodiesel and alginate from *Laminaria japonica* has been demonstrated as a viable approach to enhance the economic feasibility of seaweed farming. This process involves the extraction of mannitol for biodiesel production and the simultaneous recovery of alginate, a high-value product used in various industries (Kim et al., 2019).

Furthermore, the polysaccharides extracted from *Laminaria japonica* have been shown to possess multiple biological activities, including antioxidant, anti-inflammatory, and immunomodulatory properties, which can be harnessed for therapeutic and nutritional applications (Luan et al., 2021; Li et al., 2021). By fully utilizing the various components of *Laminaria japonica*, farmers can achieve a more sustainable and profitable cultivation system.

6 Case Studies of Sustainable *Laminaria japonica* Farming

6.1 Successful implementation examples

Several successful implementations of sustainable *Laminaria japonica* farming have been documented, showcasing the potential for environmentally friendly practices in marine agriculture. For instance, a study on the formation of environmentally persistent free radicals (EPFRs) in biochar derived from *Laminaria japonica* grown in different habitats demonstrated that the algae biomass-based biochars have similar levels and types of EPFRs as lignocellulosic-biomass-based biochars. This indicates that sustainable farming practices can produce biochars with beneficial properties for environmental applications (Huang et al., 2020). Additionally, the use of *Laminaria japonica* hydrolysate (LPH) has been shown to promote fucoxanthin accumulation and cell growth in *Phaeodactylum tricornutum*, suggesting that byproducts of *Laminaria japonica* farming can be utilized to enhance the production of valuable compounds in other marine organisms (Wang et al., 2021).

6.2 Lessons learned and best practices

From these successful implementations, several lessons and best practices have emerged. One key lesson is the importance of optimizing pyrolysis temperatures to achieve higher levels of spin concentrations in biochar, which can enhance its environmental benefits. Specifically, temperatures between 300 °C~500 °C were found to be optimal for producing biochar with higher levels of EPFRs (Huang et al., 2020). Another best practice is the low addition proportion of *Laminaria japonica* hydrolysate (1.5 ml/L), which was effective in promoting fucoxanthin accumulation and cell growth without the need for large quantities of the hydrolysate (Wang et al., 2021). These practices highlight the importance of precise control over farming and processing conditions to maximize the benefits of sustainable *Laminaria japonica* farming.

6.3 Comparative analysis

Comparing the sustainable farming practices of *Laminaria japonica* with other organic farming systems, such as those used in rice paddy landscapes, reveals several similarities and differences. Organic farming in rice paddies has been shown to support higher biodiversity and abundance of various taxonomic groups compared to conventional farming (Katayama et al., 2019). Similarly, sustainable *Laminaria japonica* farming practices, such as the production of biochar and the use of hydrolysate, contribute to environmental sustainability and the production of valuable compounds. However, while organic rice farming primarily benefits terrestrial and aquatic wildlife, sustainable *Laminaria japonica* farming has a more direct impact on marine ecosystems and the production of marine-derived products. Both systems emphasize the importance of reducing chemical inputs and optimizing management practices to achieve environmental and economic benefits.

7 Technological Advances and Future Trends

7.1 Innovations in farming techniques

Recent advancements in the cultivation of *Laminaria japonica* have focused on optimizing growth conditions and improving biomass yield. One notable innovation is the use of *Laminaria japonica* hydrolysate (LPH) to promote the accumulation of fucoxanthin in Phaeodactylum tricornutum, which has shown to enhance both cell growth and fucoxanthin production significantly (Wang et al., 2021). Additionally, the replacement of traditional starch with resistant starch derived from *Laminaria japonica* in aquaculture feed has demonstrated improvements in water quality and nutrient utilization, thereby reducing environmental pollution (Wang et al., 2023). These techniques not only enhance the efficiency of *Laminaria japonica* farming but also contribute to sustainable aquaculture practices.

7.2 Advances in monitoring and management

The monitoring and management of *Laminaria japonica* farming have seen significant improvements through the integration of advanced technologies. For instance, the use of biochar derived from *Laminaria japonica* has been studied for its environmentally persistent free radicals (EPFRs), which vary based on the pyrolysis temperature and the habitat of the algae (Huang et al., 2020). This research provides insights into the optimal conditions for biochar production, which can be used to enhance soil quality and carbon sequestration in farming systems. Moreover, the cultivation of kelp has been shown to effectively improve water quality and regulate phytoplankton communities in eutrophic bays, highlighting the importance of environmental monitoring in kelp farming (Jiang et al., 2020).

7.3 Future directions in *Laminaria japonica* farming

Looking ahead, the future of *Laminaria japonica* farming lies in the continued development of sustainable and efficient farming practices. One promising direction is the large-scale implementation of organic and low-input farming systems, which have been shown to benefit biodiversity and ecosystem services in agricultural landscapes (Katayama et al., 2019). Additionally, the integration of *Laminaria japonica* into multi-trophic aquaculture systems could further enhance nutrient recycling and reduce environmental impacts. Future research should also focus on the genetic improvement of *Laminaria japonica* strains to increase resilience to environmental stressors and enhance biomass yield. By leveraging these technological advances and innovative practices, *Laminaria japonica* farming can continue to grow sustainably and contribute to global food security and environmental health.

8 Policy and Regulatory Frameworks

8.1 National and international policies

The cultivation of *Laminaria japonica*, a significant marine economic macroalgae, is influenced by various national and international policies aimed at promoting sustainable aquaculture practices. In China, where *L. japonica* is extensively farmed, national policies emphasize the reduction of coastal eutrophication and the enhancement of marine environmental health. These policies align with international frameworks such as the United Nations Sustainable Development Goals (SDGs), particularly Goal 14, which focuses on conserving and sustainably using the oceans, seas, and marine resources. The integration of *L. japonica* farming into these policies is crucial for mitigating the environmental impacts of coastal eutrophication and promoting sustainable marine aquaculture (Xu et al., 2011).

8.2 Regulatory compliance and best practices

Regulatory compliance in the cultivation of *L. japonica* involves adhering to guidelines that ensure environmental sustainability and the health of marine ecosystems. Best practices include monitoring nutrient uptake and managing the balance of nitrogen and phosphorus in coastal waters to prevent eutrophication. Studies have shown that *L. japonica* has a significant capacity for nutrient uptake, which can be optimized under specific conditions of temperature and irradiance (Xu et al., 2011). Additionally, the production of biochar from *L. japonica* biomass must comply with regulations concerning the formation of environmentally persistent free radicals (EPFRs), which are influenced by the pyrolysis temperature and the growth environment of the algae (Huang et al., 2020). Ensuring compliance with these regulations helps in maintaining the ecological balance and promoting the sustainable use of marine resources.

8.3 Recommendations for policy improvements

To enhance the sustainability of *L. japonica* farming, several policy improvements are recommended:

(1) Enhanced Monitoring and Reporting: Implementing more rigorous monitoring and reporting systems for nutrient uptake and EPFR formation can help in better understanding and managing the environmental impacts of *L. japonica* cultivation (Huang et al., 2020; Xu et al., 2011).

(2) Research and Development Support: Increased funding and support for research on the bioremediation potential of *L. japonica* in open sea conditions can provide valuable insights into optimizing its use for coastal eutrophication control (Xu et al., 2011).

(3) International Collaboration: Strengthening international collaboration on sustainable aquaculture practices can facilitate the exchange of knowledge and technologies, promoting best practices globally.

(4) Incentives for Sustainable Practices: Providing incentives for farmers who adopt sustainable cultivation practices can encourage wider adoption and compliance with environmental regulations.

By implementing these recommendations, policymakers can ensure that the cultivation of *L. japonica* contributes positively to marine environmental health and aligns with broader sustainability goals.

9 Challenges and Opportunities

9.1 Environmental and economic challenges

The cultivation of *Laminaria japonica*, while promising, faces several environmental and economic challenges. One significant environmental concern is the formation of environmentally persistent free radicals (EPFRs) in biochars derived from *L. japonica*. These EPFRs can vary depending on the growth environment and pyrolysis temperatures, potentially impacting the surrounding ecosystems (Huang et al., 2020). Economically, the production of high-value products such as biodiesel and alginate from *L. japonica* requires efficient and cost-effective processes. Although autoclave pretreatment has shown promise, the overall economic feasibility still hinges on optimizing recovery methods and reducing production costs (Kim et al., 2019).

9.2 Opportunities for innovation and improvement

Despite these challenges, there are numerous opportunities for innovation and improvement in the cultivation and utilization of *L. japonica*. For instance, the addition of *Laminaria japonica* hydrolysate (LPH) has been shown to significantly enhance the production of fucoxanthin, a compound with notable biological activities. This method not only boosts fucoxanthin accumulation but also promotes cell growth, making it a viable strategy for large-scale production (Wang et al., 2021). Additionally, the co-production of biodiesel and alginate presents a dual-benefit approach, enhancing the economic viability of *L. japonica* farming by producing both energy and high-value products simultaneously (Kim et al., 2019).

9.3 Collaboration and stakeholder engagement

Effective collaboration and stakeholder engagement are crucial for addressing the challenges and harnessing the opportunities in *L. japonica* farming. Engaging with researchers, industry stakeholders, and policymakers can facilitate the development of sustainable practices and innovative technologies.

For example, understanding the role of *L. japonica* polysaccharides in alleviating metabolic syndrome through gut microbiota modulation can open new avenues for its use as a functional food supplement, thereby expanding its market potential (Duan et al., 2019). Collaborative efforts can also focus on optimizing cultivation techniques and improving the environmental impact of *L. japonica* farming, ensuring a balance between economic gains and ecological sustainability.

10 Concluding Remarks

The research on *Laminaria japonica* has revealed several significant findings related to its sustainable cultivation and environmental impact. Studies have shown that the habitat of *L. japonica* influences the formation of environmentally persistent free radicals (EPFRs) in biochars, with different temperatures affecting the levels and types of EPFRs produced. Additionally, the soluble dietary fiber (SDF) derived from *L. japonica* has demonstrated beneficial effects in regulating type 2 diabetes in mice, including improved glucose and cholesterol absorption and modulation of gut microbiota. Polysaccharides from *L. japonica* have also been found to alleviate metabolic syndrome by normalizing gut microbiota. Furthermore, daily intake of iodine-reduced kelp powder has been shown to reduce body fat percentage in overweight individuals without affecting thyroid function. Fermented *L. japonica* has exhibited stronger antioxidant and anti-inflammatory activities compared to its unfermented counterpart, providing protection against UVB-induced oxidative stress and inflammation. Replacing starch with resistant starch from *L. japonica* in fish feed has improved water quality and nutrient utilization, reducing nitrogen and phosphorus emissions. Insoluble dietary fiber from *L. japonica* has ameliorated obesity-related features by modulating gut microbiota dysbiosis. Fermented *L. japonica* extract has also been shown to ameliorate physical stress-induced reduction in neurogenesis. Lastly, *L. japonica* hydrolysate has been found to promote fucoxanthin accumulation in Phaeodactylum tricornutum, enhancing its production, and the sterols isolated from *L. japonica* have demonstrated significant anti-inflammatory and antioxidant activities.

The sustainable cultivation of *Laminaria japonica* is crucial for maximizing its environmental and health benefits. Sustainable practices ensure that the cultivation of *L. japonica* does not negatively impact marine ecosystems and maintains the balance of nutrients in the water. By optimizing the conditions for *L. japonica* growth, such as selecting appropriate habitats and controlling pyrolysis temperatures, the production of beneficial biochars with desirable EPFR levels can be achieved. Additionally, utilizing byproducts of *L. japonica*, such as soluble dietary fiber, for functional foods can reduce waste and enhance the economic value of this seaweed. Sustainable practices also involve the use of *L. japonica* in aquaculture to improve water quality and nutrient utilization, thereby reducing environmental pollution. Overall, sustainable cultivation practices not only contribute to environmental conservation but also enhance the health benefits and economic potential of *L. japonica*.

Future research should focus on further exploring the potential health benefits of *Laminaria japonica* and its derivatives. Investigating the mechanisms underlying the beneficial effects of *L. japonica* on metabolic syndrome, diabetes, and obesity can provide valuable insights for developing functional foods and supplements. Additionally, optimizing the fermentation processes of *L. japonica* to enhance its antioxidant and anti-inflammatory properties can lead to the development of more effective therapeutic agents. Research should also aim to improve the sustainable cultivation practices of *L. japonica*, such as identifying optimal growth conditions and minimizing environmental impacts. Furthermore, exploring the potential of *L. japonica* hydrolysate in promoting the production of valuable compounds like fucoxanthin can open new avenues for its industrial applications. Lastly, the identification and characterization of bioactive compounds in *L. japonica*, such as sterols, can contribute to the development of novel anti-inflammatory and antioxidant therapies. By addressing these research areas, the full potential of *Laminaria japonica* can be harnessed for environmental sustainability and human health.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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