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Seaweed and the applicability of freeze drying techniques

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Seaweed, often considered an overlooked resource, are marine algae with many applications in various industries. The many species of seaweed possess a range of nutritional values, environmental benefits, and their versatility make them an attractive subject of research and development. One promising method for preserving and utilising seaweed effectively is freeze drying. This review explores the world of seaweed, its properties, applications, and the potential of freeze-drying techniques in harnessing the above benefits. The review examines the freeze-drying process and discusses its applicability and advantages in preserving seaweed as a sustainable resource. The discussion also includes the diverse uses of seaweed, from culinary applications to pharmaceuticals and beyond, highlighting the potential of freeze-drying to unlock seaweed's full potential

KEYWORDS

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1 Introduction

Seaweed, often overlooked and undervalued, is a marine resource with much potential. With a rich nutritional profile, environmental benefits, and a wide range of applications, seaweed species have attracted attention in various industries. Among the many methods of preserving and utilizing seaweed, freeze-drying stands out as a promising technique. This review examines the properties, applications, and the potential of freeze drying to harness its benefits effectively. From its role in food preparations to pharmaceuticals, agriculture, and sustainable development, seaweed presents many possible uses. Freeze drying, with its ability to retain essential seaweed characteristics, plays a crucial role in realizing these potentials.

2 Seaweed: a valuable marine resource

2.1 Nutritional composition

Seaweed is a collective term for marine algae that are found in various forms worldwide. It is rich in essential nutrients, making it a valuable addition to the human diet. The nutritional composition of seaweed varies depending on the species and environmental conditions. Still, it commonly includes vitamins (e.g., A, C, B-vitamins), minerals (e.g., iodine, calcium, magnesium), dietary fibres, and essential fatty acids (Holdt and Kraan, 2011). Iodine, in particular, is abundant in seaweed and is essential for thyroid function. The presence of these nutrients makes seaweed a nutritious option for vegetarians and vegans.

Moreover, seaweed contains unique compounds such as phycobiliproteins, phycocyanins, and fucoidans with potential health benefits. These bioactive compounds have antioxidant, anti-inflammatory, and antiviral properties (Kumar et al., 2008). The rich nutritional profile of seaweed has sparked interest in its consumption as a superfood, promoting health and well-being.

2.2 Environmental benefits

Seaweed is not only beneficial for human consumption but also for the environment. It plays a significant role in marine ecosystems by providing habitat and food for various marine species. Moreover, seaweed is known for its ability to absorb and store carbon dioxide (CO₂) from the atmosphere. This process, called carbon sequestration, helps mitigate the effects of climate change by reducing the concentration of greenhouse gases in the atmosphere (Filbee-Dexter et al., 2023). Seaweed also contributes to biodiversity conservation by acting as a refuge for many marine organisms, including fish, crustaceans, and molluscs.

2.3 Versatile applications

Seaweed's versatility extends beyond nutrition and environmental benefits. It has a wide range of applications in various industries, including food, pharmaceuticals, agriculture, and cosmetics. The unique properties of seaweed, such as its gelling ability, bioactive compounds, and texture-enhancing qualities, make it a valuable ingredient in the food industry. Seaweed extracts are used as thickeners, stabilizers, and emulsifiers in a wide array of products, from ice cream to salad dressings and carbonated beverages (Alba and Kontogiorgos, 2019).

Seaweed is also gaining attention in the pharmaceutical and healthcare sectors. Compounds extracted from seaweed, such as fucoidans and carrageenans, have been studied for their potential in drug delivery, wound healing, and as dietary supplements (Neamtu et al., 2022). In agriculture and aquaculture, seaweed is used as a soil conditioner, animal feed, and a means of reducing pollution through bioremediation (Michalak, 2020).

3 Freeze drying: a novel preservation technique

3.1 The freeze drying process

Freeze drying, also known as lyophilization, is a preservation technique that removes moisture from a substance while maintaining its structure, flavour, and nutritional properties. The process involves freezing the material at low temperatures and then subjecting it to a vacuum, allowing the frozen water to sublime (change directly from a solid to a gas) without passing through the liquid phase. This unique process preserves the integrity of the product, with minimal denaturation of proteins compared to other drying techniques, making it an attractive option for preserving delicate materials like seaweed (Albers et al., 2021).

The freeze-drying process can be broken down into several key stages:

- a. Freezing: The initial step involves rapidly freezing the material, which forms ice crystals within it.
- b. Primary Drying: Under reduced pressure, heat is applied to the frozen material, causing the ice to sublime, without heating the product itself, leaving behind a porous structure.
- c. Secondary Drying: In this stage, residual moisture is removed, typically at a slightly higher temperature.
- d. Final Packaging: The freeze-dried material is sealed in a moisture-resistant package to prevent rehydration and spoilage (Nowak and Jakubczyk, 2020).

3.2 Advantages of freeze drying

Freeze drying offers several advantages that make it suitable for preserving seaweed:

- a. Preservation of Nutritional Value: Unlike traditional drying methods, freeze drying preserves the nutritional content of the temperature-sensitive bioactives within the product, including vitamins, minerals, and bioactive compounds (Shofian et al., 2011).
- b. Minimal Loss of Flavour and Aroma: Freeze drying helps maintain the often vibrant flavour and aromas of the seaweed, often concentrating the flavour by removing the dilution effect of the moisture, making it appealing for culinary applications (Stévant et al., 2018).
- c. Extended Shelf Life: Removing water during freeze drying reduces the risk of microbial growth and enzymatic reactions, significantly extending the product's shelf life (Alp and Bulantekin, 2021).
- d. Reduced Weight and Volume: Freeze drying reduces the weight and volume of the seaweed, making it easier to transport and store (Prosapio et al., 2017).

- e. Rehydration Capability: Freeze-dried seaweed can be easily rehydrated with water, restoring it to its original form, which is valuable for both consumers and industrial applications (Cox et al., 2012).
- f. Minimized Environmental Impact: Modern freeze-drying equipment facilitates an energy-efficient preservation method with a lower environmental impact than other techniques, such as canning or drying with heat (Joel et al., 2023).

4 The applicability of freeze drying techniques in seaweed preservation

4.1 Retaining nutritional value

One of the primary advantages of using freeze-drying techniques in seaweed preservation is the retention of its nutritional value. Seaweed is renowned for its rich content of vitamins, minerals, and unique bioactive compounds. Traditional drying methods, such as dehydration, sun drying or hot air drying, often lead to the loss of these essential nutrients due to exposure to heat and oxygen. In contrast, freeze drying minimises the damage caused by high temperatures, preserving the seaweed's nutritional profile (Abdollahi et al., 2019).

Seaweed, in its freeze-dried form, can be a valuable source of dietary iodine, which is essential for thyroid health. Furthermore, the bioactive compounds found in seaweed, like fucoidans and phycocyanins, remain intact during the freeze-drying process, allowing them to retain their potential health benefits (El-Beltagi et al., 2022). This makes freeze-dried seaweed an attractive ingredient for nutraceuticals and dietary supplements.

4.2 Reducing weight and volume

Another significant benefit of freeze drying is the reduction in weight and volume of the seaweed. The removal of moisture during the freeze-drying process reduces the overall mass of the product, making it more convenient for storage, transportation, and use. This property is particularly important when considering seaweed for culinary applications, as it simplifies logistics and enhances the shelf space efficiency of products containing seaweed (Peñalver et al., 2020).

4.3 Extending shelf life

The extended shelf life of freeze-dried seaweed is a valuable attribute, especially in the context of food products. The removal of water, which is a key factor in microbial growth and enzymatic reactions, significantly reduces the risk of spoilage. This means that freeze-dried seaweed products can remain fresh and safe for consumption for an extended period. This is not only convenient for consumers but also beneficial for the food industry, as it reduces food waste and the need for preservatives or maintenance of a cold

chain transport and storage system (Peñalver et al., 2020). A comparative 2023 study on the effect of different drying techniques on phenolic compounds in Australian beach-cast brown seaweeds (*Sargassum* sp., *Ecklonia radiata* *Cystophora* sp.) consistently demonstrated high phenolic and antioxidant properties in freeze dried samples (Subbiah et al., 2023).

4.4 Minimizing environmental impact

Freeze drying is recognized for its environmental advantages when compared to other preservation methods. The energy-efficient nature of the freeze-drying process results in lower greenhouse gas emissions and reduced energy consumption, especially where modern natural refrigerants such as carbon dioxide and heat recovery technologies are embodied in the design of the equipment used. This is particularly relevant in the context of sustainability and environmental responsibility. As the world strives to reduce its carbon footprint, freeze-drying stands out as a method that aligns with these goals (Kaveh et al., 2023). It should be stated that the benefits of freeze-drying are cost effective, when applied to food production, the overall benefits of freeze-drying represent a small contribution to overall energy consumption in global terms.

5 Culinary applications of freeze-dried seaweed

Seaweed has a long history of culinary use in various cultures around the world, especially in East and Southeast Asia. Its unique flavours, textures, and umami-rich profiles have made it a popular ingredient in traditional dishes. With the advancements in freeze-drying technology, seaweed is now making its way into the culinary world on a global scale.

5.1 Seaweed snacks

Freeze-dried seaweed is gaining popularity as a healthy and flavoursome snack. The crispy, lightweight texture of freeze-dried seaweed provides a satisfying alternative to conventional potato chips. These snacks are often seasoned with various flavours, such as sesame, wasabi, or soy sauce, enhancing their appeal to consumers looking for innovative and healthy snacking options. Additionally, freeze-drying retains the umami taste of seaweed, making it an ideal component for flavourful snacks (Coleman et al., 2023).

Examples of commercially available products are detailed below:

Amanofuzu freeze dry seaweed soup: These are seaweed snacks and are available in various flavours like original, wasabi, and onion.

Marukome Freeze Dried Granulated Instant Miso Soup: a seasoned miso seaweed soup available in different flavours.

Wakame Seaweed Flakes (*Undaria pinnatifida*).

5.2 Seasonings and condiments

Seaweed extracts and powders, obtained through freeze-drying, have become sought-after ingredients for enhancing the flavour of various dishes. These seaweed-derived seasonings and condiments add a depth of umami and savoury notes to soups, sauces, and marinades. They are a versatile addition to modern cuisines, catering to diverse taste preferences. The convenience and long shelf life of freeze-dried seaweed products make them a valuable resource for culinary innovation. Examples include:

Furikake: A Japanese seasoning blend containing seaweed, sesame seeds, and freeze-dried fish flakes, often used to sprinkle over rice or noodles.

Kelp Powder: Ground freeze-dried kelp seaweed that can be used as a seasoning in soups, stews, and sauces to add a savoury flavour.

Seaweed Flakes: Flakes of freeze-dried seaweed that can be used as a seasoning for salads, soups, and stir-fries (Mamat et al., 2013)..

5.3 Culinary innovations

Chefs and food innovators are exploring freeze-dried seaweed's potential to create new culinary experiences. For instance, it can be rehydrated and used as a wrap for sushi, a topping for salads and seafood dishes, or as a component in fusion cuisine. It can also be rehydrated with an entirely different liquid than the water removed, creating a new novel flavour profile. Freeze-dried seaweed can also be incorporated into baked goods, adding unique flavours and textures to bread, crackers, and pastries. Its adaptability in the kitchen is expanding the horizons of culinary exploration and enriching the world of gastronomy. Examples include:

Seaweed Pasta: Pasta made from freeze-dried seaweed or seaweed-infused flour, offering a unique flavour and added nutritional benefits.

Seaweed Butter: Butter infused with freeze-dried seaweed flakes or seaweed extract, adding a savoury umami flavour to dishes.

Seaweed Salsa: Salsa made with seaweed as a primary ingredient, providing a salty and slightly briny flavour profile (Mamat et al., 2013).

6 Seaweed in the pharmaceutical and healthcare industries

The healthcare and pharmaceutical sectors are increasingly recognizing the therapeutic potential of seaweed-derived compounds. Freeze drying plays a vital role in preserving these compounds, making them available for various applications.

6.1 Medical dressings and wound care

Seaweed extracts, such as alginate and carrageenan, have unique properties that make them valuable for wound care and

medical dressings. These compounds can absorb exudates from wounds, provide a moist healing environment, and have antimicrobial properties. Freeze drying ensures the stability of these seaweed-derived materials, making them suitable for medical applications. In addition, the porous structure created by freeze-drying allows for the controlled release of active compounds in medical dressings, contributing to improved wound healing (Aderibigbe and Buyana, 2018). An extensive review of alginate dressings is available which discusses freeze-dried seaweed extracts used in alginate wound dressings for their ability to promote wound and burn healing and reduce inflammation (Agarwal et al., 2011).

6.2 Drug delivery systems

Seaweed extracts and polysaccharides, when properly processed through freeze drying, can be used in drug delivery systems. These systems allow for the controlled release of drugs or bioactive compounds. The freeze-dried matrices provide a stable environment for drug encapsulation and release, ensuring the drug's efficacy and safety. This technology can potentially revolutionise pharmaceutical formulations, offering precise control over drug release rates (Klojđová et al., 2023).

6.3 Nutraceuticals and supplements

The freeze-drying of seaweed extracts and powders facilitates the creation of nutraceutical and dietary supplement products. These supplements provide a convenient way for consumers to access the health benefits of seaweed, such as iodine and bioactive compounds, in a concentrated and easily consumable form. Freeze-dried seaweed supplements ensure the stability of these compounds, preserving their efficacy and health-promoting properties (Lomartire et al., 2021).

7 Seaweed in agriculture and aquaculture

Seaweed is not only limited to human consumption and pharmaceuticals; it also has diverse applications in agriculture and aquaculture.

7.1 Soil conditioners

Seaweed-based products, derived from freeze-dried seaweed, are used as soil conditioners and fertilizers in agriculture. These products enhance soil structure, water retention, and nutrient availability, improving overall soil health. Freeze-dried seaweed's low weight and volume are advantageous for transport and application in agriculture, making it an eco-friendly choice for sustainable farming practices (Ali et al., 2021).

7.2 Animal feed

Freeze-dried seaweed is a valuable ingredient in animal feed for both terrestrial and aquatic animals. Seaweed contains essential nutrients and bioactive compounds that can improve the health and growth of livestock, poultry, and aquatic species. Its inclusion in animal diets can enhance the quality of meat, eggs, and seafood, while also benefiting the animals' overall well-being. The ease of handling and storage of freeze-dried seaweed makes it a practical choice for animal feed formulations (Kinley et al., 2020).

7.3 Bioremediation

Seaweed's ability to absorb and store pollutants from the environment has led to its use in bioremediation efforts. Freeze-dried seaweed can be employed to remove heavy metals and other contaminants from polluted water bodies. The absorbed pollutants can be recovered from the seaweed, allowing for both environmental clean-up and the potential recycling of valuable resources (Farghali et al., 2023).

8 The role of seaweed in sustainable development

Seaweed's versatility and its potential applications in various industries contribute to sustainable development in multiple ways.

8.1 Carbon sequestration

Seaweed's ability to absorb and store carbon dioxide from the atmosphere is a powerful tool for mitigating climate change. As the world seeks to reduce carbon emissions and slow global warming, the cultivation of seaweed for carbon sequestration is gaining attention. Seaweed farms not only help remove CO₂ from the atmosphere but also provide habitat for marine life, promoting biodiversity and ecosystem restoration (Sultana et al., 2023).

8.2 Biodiversity conservation

Seaweed beds and underwater forests are essential habitats for various marine species, including fish, invertebrates, and algae. By promoting the conservation of these ecosystems, the cultivation and sustainable harvesting of seaweed contribute to biodiversity preservation. Seaweed farms can provide refuge for endangered species and restore damaged marine environments (Xiao et al., 2021). Farghall et al. in 2022 published a wide-ranging and comprehensive review that discusses the roles that seaweeds can play in climate mitigation, wastewater treatment, bioenergy,

bioplastic, biochar, food, pharmaceuticals, and cosmetics (Farghali et al., 2023).

8.3 Economic opportunities

The seaweed industry offers economic opportunities to coastal communities and individuals involved in seaweed farming, processing, and product development. These opportunities support livelihoods, reduce poverty, and strengthen local economies. Additionally, the export of seaweed-based products contributes to international trade and economic growth (Rao and Ravishankar, 2022).

9 Challenges and future prospects

While the potential of seaweed and freeze drying is large, several challenges need to be overcome. These challenges include:

- a. Sustainability: The sustainable cultivation and harvesting of seaweed are critical to prevent overexploitation and ecosystem damage. The proven ability to remove harvested seaweed from the cold chain in developing countries via freeze-drying may allow product to reach premium markets in good saleable condition i.e. freeze-drying provides the ability to create a value-add premium to a perishable product regardless of ambient temperatures.
- b. Supply Chain Logistics: Developing efficient supply chains for seaweed, from farming to processing to end-products, is essential for the industry's growth. Again, freeze drying allows seaweed to be shipped outside of the cold chain which often does not exist outside of large cities in developing countries.
- c. Regulatory Frameworks: Establishing and enforcing regulations to ensure product safety, quality, and environmental responsibility are needed.
- d. Consumer Awareness: Increasing consumer awareness of the benefits of seaweed and the utility of freeze-dried seaweed products is crucial to increase usage of this product.

The prospects of seaweed and freeze drying are promising, as ongoing research and innovation address the above challenges. The seaweed industry is expected to grow, offering sustainable solutions to various global challenges, including food security, environmental conservation, and economic development (Rebours et al., 2014).

10 Conclusion

Seaweeds are a versatile marine resource with applications in various industries, from food and pharmaceuticals to agriculture and environmental conservation. Freeze drying, a preservation

technique that retains the nutritional value and characteristics of seaweeds, plays a vital role in unlocking its full potential. Freeze-dried seaweed products have found their way into the culinary world as healthy snacks, seasonings, and innovative ingredients. In the pharmaceutical sector, seaweed extracts and compounds are being used in wound care, drug delivery, and dietary supplements. Seaweed's role in agriculture and aquaculture offers sustainable solutions for soil improvement, animal feed, and pollution control (Farghali et al., 2023).

Moreover, seaweed cultivation contributes to sustainable development by sequestering carbon, conserving biodiversity, and generating economic opportunities for coastal communities. While challenges exist, ongoing research and industry innovation are addressing these issues, paving the way for a brighter future for seaweed and freeze-drying. Seaweed's journey from the ocean to our plates, pharmacies, and farms is exciting, offering a range of benefits for humanity and the planet.

The combination of seaweed's diverse properties and the applicability of freeze-drying techniques opens the door to increased nutritional possibilities, ensuring that this underutilized marine resource can provide value in the modern age. As our understanding of seaweed and its potential continues to grow, we can harness its benefits responsibly and sustainably thereby creating a more resilient future for our world and its inhabitants (Rao and Ravishankar, 2022).

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