Literature Review of Nutrient, Bioactive, Food Safety, and Processing Aspects of Key Kelp Species: *Alaria marginata, Nereocystis luetkeana, and Saccharina latissima*

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Introduction

Kelp, a diverse group of brown algae seaweeds, has in recent years garnered significant attention for its nutritional and bioactive properties. Requiring little to no agricultural inputs, they are also a promising candidate for building more sustainable food systems and regional economies. This literature review examines the nutrient profiles, bioactive compounds, food safety considerations, and processing characteristics of three select kelp species: *Alaria marginata* (Ribbon Kelp), *Nereocystis luetkeana* (Bull Kelp), and *Saccharina latissima* (Sugar Kelp). These three species were chosen for their unique ability to thrive in Alaskan waters. The review aims to identify the most viable species for large-scale production, providing a comprehensive comparison to guide future efforts in kelp-based food innovation.

Part 1: Nutritional Profiles and Health Benefits of Select Kelps

The three species have a similar nutritional profile; it may be more challenging for bull kelp because there is no recent data available, but there are a lot of commonalities between the three. Summary of health properties that apply to the three kelp species:

- *Anti-inflammatory*
- *Promote thyroid function*
- *Antioxidant*
- *Gut health - prebiotic*
- Cardiovascular health by reducing cholesterol levels, lowering blood pressure and *weight management*
- Cardiovascular, and muscle health

Alaria marginata (Ribbon Kelp)

Alaria marginata, commonly known as Ribbon Kelp, is recognized for its nutritional richness (Table 1) and diverse bioactive compounds (Table 2) that contribute to health promotion (Freitag, 2017). This seaweed is particularly noted for its substantial content of antioxidant compounds and polysaccharides, believed to enhance immune function and exhibit anti-inflammatory properties (MacArtain et al., 2007; Usov, Smirnova, & Klochkova, 2001). Its nutritional profile includes significant levels of vitamins and minerals critical for various bodily functions, including vitamin K, iodine, and calcium (MacArtain et al., 2007).

Alaria marginata is rich in bioactive compounds such as fucoidan, known for its anti-inflammatory, anticoagulant, antiviral, and anticancer properties (Fitton et al., 2015; Cumashi et al., 2007), and fucoxanthin, linked to weight management and reduced risks of diabetes and heart disease (Maeda et al., 2005; D'Orazio et al., 2012). Laminarin and alginate, both found in this seaweed, contribute to gut health,

appetite control, and wound healing (Jiao et al., 2011; Lee & Mooney, 2012; Draget et al., 2005). The inclusion of *Alaria marginata* in diets is associated with several health benefits, primarily due to its antioxidant capabilities that help mitigate oxidative stress (Journal of Agricultural and Food Chemistry, 2013). Studies have shown its strong inhibitory effects on enzymes that break down dietary starch, suggesting its potential in managing blood sugar levels (Marine Drugs, 2014). The phenolic compounds and polysaccharides in *Alaria marginata* also play significant roles in health promotion, nourishing colonic microbiota and providing overall health-enhancing properties (Advances in Food and Nutrition Research, 2012).

Nereocystis luetkeana (Bull Kelp)

Nereocystis luetkeana, commonly known as bull kelp, is a brown macroalgae prevalent along the coasts of the northeastern Pacific Ocean. Bull kelp provides significant amounts of nutrients (Table 1) and minerals such as calcium, magnesium, and potassium, crucial for bone, cardiovascular, and muscle health (Holdt & Kraan, 2011; Rupérez, 2002; Dawczynski et al., 2007). The bioactive compounds in bull kelp (Table 2) exhibit potent antioxidant properties, reducing oxidative stress and potentially lowering the risks of chronic diseases such as cancer and heart disease (Wang et al., 2009; Shannon & Abu-Ghannam, 2017). Its polysaccharides, such as fucoidans, possess anti-inflammatory properties that may help mitigate inflammation-related disorders (Fitton et al., 2015; Li et al., 2016). The fiber and essential fatty acids in bull kelp contribute to cardiovascular health by reducing cholesterol levels and lowering blood pressure (Kendall et al., 2010). Fucoxanthin in bull kelp has shown potential in regulating blood sugar levels and enhancing insulin sensitivity, offering benefits for individuals with type 2 diabetes (Maeda et al., 2005; Mikami & Hosokawa, 2013). The diverse bioactive compounds, including fucoidan, fucoxanthin, laminarin, and alginate, enhance bull kelp's therapeutic and nutritional potential.

Saccharina latissima (Sugar Kelp)

Saccharina latissima, commonly known as sugar kelp, is celebrated for its rich nutritional composition (Table 1) and versatile culinary applications (Holdt & Kraan, 2011). Sugar kelp’s mineral profile includes calcium, magnesium, iodine, and potassium, crucial for bone, cardiovascular, and muscle health, and it provides substantial dietary fiber, promoting digestive health and aiding in weight management (Kendall et al., 2010).

Sugar kelp contains a variety of bioactive compounds (Table 2), such as phlorotannins, fucoidans, alginates, fucoxanthin, and laminarin, which exhibit antioxidant, anti-inflammatory, and antidiabetic properties (Goel et al., 2021; Baghel et al., 2023; Pérez-Lloréns et al., 2023; Lane & Kubanek, 2008; Weigel et al., 2022).

These compounds help reduce oxidative stress, lower the risks of chronic diseases, manage blood sugar levels, and improve insulin sensitivity. The rich array of vitamins and minerals in sugar kelp contributes to a healthy immune system, with elements like zinc and selenium playing crucial roles (Guiry & Guiry, 2012).

Table 1: Nutrient composition of *Alaria marginata*, *Nereocystis luetkeana*, and *Saccharina latissima*

		***Alaria marginata* (Ribbon Kelp)**				***Nereocystis luetkeana* (Bull Kelp)**				***Saccharina latissima* (Sugar Kelp)**			
Nutrient	**Function**	**Nutrients per 100 g (dry)**	**Nutrients per serving (5 g dry)**	**Daily Value (%) per 5 g serving**	**Source**	**Nutrients per 100 g (dry)**	**Nutrients per serving (5 g dry)**	**Daily Value (%) per 5 g serving**	**Source**	**Nutrients per 100 g (dry)**	**Nutrients per serving (5 g dry)**	**Daily Value (%) per 5 g serving**	**Source**
Fat	Provides energy, supports cell growth, and aids in nutrient absorption.	3.1 g	0.2 g	0.26%	MCSV	2.2 g	0.1 g	0.1%	Barta et al., 1981	2.8 g	0.1 g	0.1%	MCSV
Carbs	Primary energy source for the body and brain.	53 g	2.7 g	1%	MCSV	39.9 g	2.0 g	0.7%	Barta et al., 1981	52 g	2.6 g	1%	MCSV
Protein	Builds muscle, repairs tissues, supports immune function, and hormone production.	12.9 g	0.6 g	1.2%	MCSV	11.2 g	0.6 g	1.2%	Barta et al., 1981	11 g	0.6 g	1.2%	MCSV
Fiber	Aids digestion, promotes gut health, and regulates blood sugar.	51 g	2.6 g	9.2%	MCSV	3.7 g	0.2 g	0.7%	Barta et al., 1981	35 g	1.8 g	6.5%	MCSV
Omega 3 fatty acids	Supports heart health, reduces inflammation, and boosts brain function.	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Vitamin A	Essential for immune function, vision, and skin health.	939 ug	47.0 ug	5.20%	MCSV	ND	ND	ND	ND	65 ug	3.3 ug	0.4%	MCSV
Vitamin C	Important for the synthesis of collagen, the absorption of iron, and the maintenance of cartilage, bones, and teeth.	17 mg	0.9 mg	1%	MCSV	ND	ND	ND	ND	12 mg	3.3 mg	0.7%	MCSV
Calcium	Calcium - Vital for bone health and the functioning of muscles, nerves, and cells.	1,258 mg	63.0 mg	5%	MCSV	ND	ND	ND	ND	2,450 mg	0.6 mg	9.5%	MCSV

Iodine	Critical for thyroid function and metabolism regulation.	29,500 mg	1475 mg	983%	MCSV	ND	ND	ND	ND	278,200 ug	123 mg	9273%	MCSV
Iron	Necessary for the production of hemoglobin, which carries oxygen in the blood.	24.9 mg	1.2 mg	7%	MCSV	5.4 mg	0.3 mg	1.7%	Barta et al., 1981	22.7 mg	13910 mg	6.1%	MCSV
Magnesium	Involved in over 300 biochemical reactions in the body, including muscle and nerve function, blood glucose control, and blood pressure regulation.	755 mg	37.8 mg	9%	MCSV	121 mg	6.1 mg	1.5%	Hochroth & Pfister, 2024	770 mg	1.1 g	9.2%	MCSV
Potassium	Helps regulate fluid balance, muscle contractions, and nerve signals.	5,414 mg	271 mg	6%	MCSV	970 mg	48.5 mg	1%	Hochroth & Pfister, 2024	6,966 mg	39 mg	7.5%	MCSV
Sodium	Essential for fluid balance, nerve function, and muscle contractions.	3520 mg	176 mg	7.5%	MCSV					3,628 mg	348 mg	7.9%	MCSV
Zinc	Supports immune function, wound healing, and DNA synthesis.	3.0 mg	0.2 mg	2%	MCSV	2.1 mg	0.1 mg	1%	Barta et al., 1981	2.9 mg	181 mg	1%	MCSV

Nutrients are listed in 100g serve for comparison across other foods, and 5g to represent average dry serving size.
All nutrient values are based on dry weight.
ND (Gray box) = no data available
MCSV = Maine Coast Sea Vegetables
***** = Fresh or rehydrated; serving size 9-21 grams (ave 15 g)

Nutrients that should be highlighted from the table as they are found in high amounts: Fiber, vitamin A, calcium, and iron.
According to the limited available published data, there are no significant differences among species from a nutritional standpoint. However, there is no available data for bull kelp. Ribbon and Sugar kelp, have a similar nutritional profile, being sugar kelp higher in iodine and calcium, and Ribbon help being higher in Vitamin A.

Although research is limited on the health benefits of kelp, the following bioactive compounds and related benefits have been identified (table 2).

Table 2: Bioactive compounds found in *Alaria marginata*, *Nereocystis luetkeana*, and *Saccharina latissima*

Bioactive Compounds* Found in: *Alaria marginata, Nereocystis luetkeana,* and *Saccharina latissima*	**Possible Health Benefits of Select Kelp Species***
Phlorotannins	• **Antioxidant properties**: Helps protect cells from oxidative stress. • **Anti-inflammatory:** Helps reduce inflammation in the body. • **Antimicrobial**: Helps inhibit the growth of harmful bacteria and fungi. • **Anti-tumor**: Potential to prevent or slow the growth of cancer cells.
Fucoidans	• **Immune modulation**: Helps enhance immune system function. • **Anti-coagulant**: Helps prevent blood clot formation. • **Anti-viral**: Helps inhibit the replication of viruses. • **Anti-tumor**: Helps suppress tumor growth and metastasis.
Alginates	• **Polysaccharide, Dietary fiber**: Aids in digestion and promotes gut health. • **Weight management**: Helps enhance satiety and reduce calorie intake. • **Cholesterol-lowering**: Helps reduce blood cholesterol levels. • **Heavy metal detoxification**: Helps bind to heavy metals and facilitates their excretion.
Fucoxanthin	• **Anti-obesity:** Helps promote fat burning and weight loss. • **Anti-diabetic**:Helps improve insulin sensitivity and lowers blood sugar levels. • **Anti-inflammatory**: Helps reduce inflammation. • **Antioxidant properties**: Helps to protect cells from oxidative damage.
Laminarin	• **Immune modulation**: Helps enhance the immune response. • **Anti-coagulant**: Helps prevent blood clot formation. • **Polysaccharide, Dietary fiber**: Aids in promoting the growth of beneficial gut bacteria.

	• **Anti-tumor**: Potential to inhibit tumor growth.
*Levels can vary significantly based on species, time, amount and location of harvest Sources: Baghel et al., 2023; Brownlee et al., 2005; Kang et al., 2013; Lane & Kubanek, 2008; Li et al., 2008, 2011; Mikami et al., 2012; Ni et al., 1996; O'Sullivan et al., 2010; Pérez-Lloréns et al., 2023; Ren et al., 2012; Weigel et al., 2022	

Part 2: Food Safety Considerations of Select Kelps

Heavy Metal Levels in Kelp (See table 3)

Kelp species can accumulate heavy metals such as arsenic, cadmium, lead, and mercury from their marine environment (Table 3), possibly posing health risks if consumed in large quantities, specifically for more vulnerable populations like children (Van Netten et al., 2000; Coelho, 2022). This is an active area of emerging research and interest globally, so there is currently limited evidence, stakeholder consensus or federal or global guidance in this area. Furthermore, the interplay of food matrix, nutrients, and health outcomes is multifactorial and complex. Dietary patterns can play an active role in influencing the impacts (uptake, protection, etc) of any individual food or nutrient. For instance, emerging research suggests that dietary fibers may play a role in helping to mitigate the adverse effects of heavy metals found in seaweeds. Specific dietary fibers have been shown to reduce heavy metals absorption by binding to them in the gut. These fibers may help reduce their bioavailability and toxicity, potentially lessening the negative health impacts associated with heavy metal exposure (Román-Ochoa et al., 2024). More research is needed in this area to confirm these benefits.

Another significant area of interest around food safety and kelp centers on the question of iodine content. Kelp is known to contain very high levels of iodine, which may cause thyroid dysfunction if consumed in excess, particularly in iodine-sensitive individuals (Farebrother et al., 2019; Combet & Bouga, 2023). The recommended dietary intake (RDA) of iodine is 150 mcg for adolescents and adults, and 220 mcg for pregnant women. However, many cultural foodways have long enjoyed regular consumption of iodine-rich seaweeds without a prevalence of thyroid dysfunction, so this area requires additional research. There may be other explanations for high iodine tolerance, such as the impact of overall dietary patterns on nutrient intake and bioavailability. In addition, post-nuclear events have heightened concerns about the potential presence of radioactive isotopes in marine life, including seaweeds, which can absorb radioactive iodine and cesium from waters (Bouga & Combet, 2015).

Table 3: Heavy Metal Considerations* of *Alaria marginata*, *Nereocystis luetkeana*, and *Saccharina latissima*

		***Alaria marginata* (Ribbon Kelp)**			***Nereocystis luetkeana* (Bull Kelp)**			***Saccharina latissima* (Sugar Kelp)**		
Food Safety	**Max daily limit for an adult**	**Amount per 100 g (dry)**	**Amt per 5 g serving (ug)**	**Daily limit (%) per 5 g serving**	**Amount per 100 g (dry)**	**Amt per 5 g servin g**	**Daily limit (%) per 5 g serving**	**Amount per 100 g (dry)**	**Amt per 5 g servin g**	**Daily limit (%) per 5 g serving**
Arsenic	**21 µg**	**39.5 ug**	1.9	9%	**79 ug**	3.9	19%	**76.2 ug**	3.8	18%
Lead	**6 µg**	**0.64 ug**	0.03	1%	**0.01 ug**	0.0	0%	**0.01 ug**	0.0	0%
Cadmium	**58 µg**	**.45 ug**	0.02	0%	**2.7 ug**	0.1	0%	**2.8 ug**	0.1	0%
Mercury	**7 µg**	**7.3 ug**	0.4	5%	**0.1 ug**	0.0	0%	**0.1 ug**	0.0	0%

*species analyzed from a single source, and do not represent all seaweed species and geographies. Data not collected from Alaksan waters. All species are based on dry weight; serving size 3-7 grams (ave = 5 g)
Source: Van Netten, C., 2000.

It should still be considered in decision-making, since it is not updated.

- **Arsenic**: This heavy metal is a systemic challenge present in both terrestrial agriculture and aquaculture. Organic arsenic is often found in diverse marine environments and can accumulate in seaweed. Organic arsenic, commonly found in seafood, is less harmful than inorganic arsenic. Certain foods like brown rice contain inorganic arsenic, which is more toxic and is associated with higher health risks, including cancer and cardiovascular diseases (U.S. Government Accountability Office, 2018). Research thus far suggests levels of organic arsenic in seaweeds can and do vary widely, depending on geographic location and time of year. Food safety regulations focus on minimizing inorganic arsenic exposure due to its higher toxicity and potential adverse health effects.
    - The EPA has set a reference dose (RfD) for inorganic arsenic at 0.0003 mg/kg/day (0.3 µg/kg/day). There are currently no specific dietary recommendations or regulatory limits for organic arsenic in foods due to its lower toxicity.
        - For an average adult weighing 70 kg, this translates to a safe daily intake of ~ **21 µg/day.**
    - Adverse effects: cancer, cardiovascular diseases, neurological effects, diabetes, miscarriage during pregnancy.
    - Causes**:** Polluted waters from industrial activities and agricultural pesticides.
- **Cadmium**: This heavy metal is typically found in lower concentrations in marine algae, but it's essential to monitor due to its harmful effects on kidney function and bone density over prolonged exposure.
    - The Joint FAO/WHO Expert Committee on Food Additives (JECFA) has established a provisional tolerable monthly intake (PTMI) for cadmium at 25 µg/kg body weight.
        - This translates to a safe daily intake of about 0.83 µg/kg body weight. For an average adult weighing 70 kg, this is ~ **58 µg/day.**
    - Adverse effects: cancer, renal failure, osteoporosis, taste dysfunction.
    - Causes: manufacturing materials
- **Lead**: This heavy metal is less commonly found in significant amounts in marine algae, but contamination can occur through environmental pollution. Preparation methods, such as soaking and blanching, can significantly reduce the lead content in kelp. These processes help remove contaminants and make kelp more safe for consumption (Zhang et al. 2019).
    - The FDA has set the maximum daily intake level for lead from food at **~ 6 µg/day** for adults (US FDA 2023).
    - Adverse effects: kidney diseases, hypertension, and reproductive and neurocognitive problems.
    - Causes: household activities

- **Mercury**: This heavy metal is usually present in trace amounts in kelp, but certain environmental conditions can lead to higher levels, posing risks of neurotoxicity.
    - The EPA's reference dose (RfD) for methylmercury is 0.1 µg/kg/day.
        - For an average adult weighing 70 kg, this translates to a safe daily intake of about **~7 µg/day**
    - Adverse effects: neurotoxin, poisonous to all nerve tissues.
    - Causes: coal production, mining, and agricultural pollution.

Arsenic in Kelp

Recent studies (Taylor et al., 2017) have focused on the arsenic content in seaweed and its potential health implications. The research revealed that seaweeds contain significant levels of arsenosugars, which are organic arsenic compounds found in marine algae and seaweed. Arsenosugars are less toxic than inorganic arsenic, which is a known human carcinogen. Studies suggest that while seaweed consumption introduces arsenic into the human diet, the health risks might be lower than previously thought due to the higher percentage of organic vs inorganic arsenic, although caution is still advised due to the variability in arsenic species and their toxicities. (Taylor et al., 2017). Further, the metabolism and toxicology of arsenosugars are not well understood, and there is a lack of data on toxicity, chronic exposure, and human populations.

To mitigate these food safety concerns, it's essential to source kelp from clean and unpolluted waters, preferably from areas with minimal industrial activity and agricultural runoff. Regular testing for heavy metals, microbial pathogens, and other contaminants can help ensure the safety of kelp products intended for human consumption.

Iodine in Kelp

According to the National Health and Nutrition Examination Survey (NHANES), iodine deficiency can indeed be a shortfall nutrient for some people, particularly pregnant and breastfeeding women, people following a plant-based diet, and individuals in regions with low iodine levels in the soil or who do not consume iodized salt (and choose all natural salts instead). A study published in the American Journal of Clinical Nutrition found that pregnant women in the U.S. have mild to moderate iodine deficiency, which could have adverse effects on fetal neurodevelopment (Zimmermann & Jooste, 2009). The NIH (2024) highlights that certain foods, like soy, cassava, and cruciferous vegetables (e.g., cabbage, broccoli, and cauliflower) contain goitrogens, which can interfere with iodine uptake in the thyroid. While the majority of the U.S. population consumes adequate iodine and a variety of foods, incorporating kelp into the diet can be a valuable source of iodine, especially for those seeking to optimize their intake. Kelp is rich in iodine and can help ensure sufficient levels, supporting thyroid health and preventing deficiency. Including kelp in the diet can be a natural and effective way to boost iodine levels, particularly for individuals at risk of deficiency or looking to enhance their nutritional intake. However, there is not strong evidence that seaweed should be avoided by pregnant women or children, particularly when consumed in moderation.

Seaweed consumption, particularly in cultures with a tradition of consuming seaweed-rich diets, offers insights into the health implications of high iodine intake. In Japan, where seaweed is a dietary staple, studies have shown that, despite the high iodine content in seaweed, there are no apparent adverse effects on thyroid function among the general population (Yokoyama et al., 2012). Traditional diets may help mitigate the adverse impacts of seaweed consumption by incorporating a diverse range of foods that may counterbalance potential toxins and optimize nutrient absorption for a more harmonious balance (Miyamoto et al., 2011). For example, traditional Japanese diets include rice, miso soup, goitrogenic foods such as cruciferous vegetables, and fermented foods alongside seaweed. These foods may help reduce the bioavailability of substances like excessive iodine content and heavy metals present in seaweed, thus minimizing their negative effects on health. More research is needed in this area to fully understand these mechanisms of action.

Techniques exist to reduce the iodine content in seaweeds. Studies have shown water blanching as an effective means to reduce iodine content. For example, blanching at temperatures of 45-80°C for durations of 30-120 seconds can significantly decrease iodine levels, with the most effective condition being 80°C for 120 seconds, thus reducing iodine content from 4605 mg/kg to 293 mg/kg. This method also maintains other valuable nutrients, such as essential minerals, vitamins, lipids, and proteins (Nielsen et al., 2020).

However, it is important to note that excessive consumption of seaweed, especially certain types with exceptionally high iodine content, depending on dietary patterns, can lead to iodine toxicity and adverse health effects (Farebrother et al., 2019). Therefore, while seaweed can be a valuable source of iodine and other nutrients, moderation is key to avoiding potential risks associated with excessive iodine intake. To optimize the benefits and mitigate risks, it's advisable to incorporate a diverse range of seaweeds in your diet in moderation: aim for 3-7 grams of dried seaweed or 9-21 grams of fresh or rehydrated seaweed, consumed 1-2 times weekly.

Part 3: Environmental Influence of Alaskan Waters on Kelp Production

In consideration of the above (Part 2), it’s important to underscore that current research on food safety of kelp does not incorporate contemporary Alaskan grown kelp species, which may help reduce food safety concerns. Up to date data on Alaska kelp nutrient and food safety profiles will be invaluable to provide confidence on the best health and nutrition messaging direction, and engender trust among consumers regarding the value of choosing Alaska kelp.

The environmental conditions of Alaskan waters significantly influence the nutritional value and safety of cultivated kelp. Several factors contribute to this:

Water Quality
The clean and relatively unpolluted nature of Alaskan waters ensures the high quality of cultivated kelp. Clean water free from industrial pollutants, agricultural runoff, and urban contaminants helps maintain the nutritional integrity and safety of kelp harvested from these waters (Smith et al., 2020).
Nutrient Availability
Alaskan waters are rich in nutrients due to factors such as ocean currents and nutrient-rich waters from glaciers and snowmelt. These nutrient inputs provide essential minerals and trace elements that contribute to the nutritional value of kelp (Wiltshire et al., 2010). Kelp harvested from nutrient-rich waters may have higher concentrations of vitamins, minerals, and other beneficial compounds compared to kelp from less fertile regions.
Low Industrial Activity
Alaskan waters generally have lower levels of anthropogenic pollution compared to some coastal regions with heavy industrial activity. The absence of industrial discharges and contamination from manufacturing processes reduces the risks of heavy metal and chemical contamination in cultivated kelp (Garza et al., 2015). This enhances the safety and purity of kelp products sourced from Alaskan waters.
Climate and Environmental Conditions
The cold, nutrient-rich waters of Alaska create an ideal habitat for kelp growth. The cool temperatures and ample summer sunlight support robust kelp forests, allowing the plants to thrive and accumulate nutrients (Konar et al., 2019). Additionally, the absence of significant pollution sources helps maintain the ecological balance necessary for healthy kelp ecosystems.
Regulatory Oversight
Alaska has stringent regulations and management measures built into its state constitution to protect its marine environment and seafood resources. These regulations may include monitoring programs, harvest quotas, and quality control measures to ensure that cultivated kelp meets safety standards and is sustainably managed (Alaska Department of Fish and Game, 2023).

All of these considerations are part of the reason Alaska seafood's industry currently enjoys a robust reputation for trust by consumers in other categories such as salmon.

Part 4: Commercialization of Kelp Species

- *Alaria marginata* (ribbon kelp): Ribbon kelp is known for its long, ribbon-like fronds and is commonly found in subtidal zones. It has a mild flavor and is

often used in salads, soups, and stir-fries. Ribbon kelp has potential for commercialization due to its culinary versatility and relatively easy cultivation.

- *Nereocystis luetkeana* (bull kelp): Bull kelp is characterized by its large, bulbous pneumatocysts and long, flexible stipes. It grows in shallow coastal waters and can form dense kelp forests. Bull kelp has various industrial applications, including in the production of alginates, as well as culinary uses such as in soups and pickles.
- *Saccharina latissima* (sugar kelp): Sugar kelp is a brown algae with broad, leathery fronds. It is prized for its sweet, umami flavor and high nutritional content. Sugar kelp is commonly used in salads, sushi, and as a flavor enhancer in various dishes. It also has potential for biofuel production and as a source of biostimulants for agriculture.

Top Species for Commercialization: *Saccharina latissima* (Sugar Kelp)

Based on the literature review and analysis, *Saccharina latissima* (sugar kelp) rises to the top for prioritization for commercialization among the three kelp varieties—*Alaria marginata* (ribbon kelp), *Nereocystis luetkeana* (bull kelp), and Saccharina latissima (sugar kelp).

- **Robust Nutritional Profile**: Sugar kelp boasts a robust nutritional profile, including minerals like calcium, magnesium, iron, and potassium, which are crucial for metabolic health, immune function, and cardiovascular health. In addition, sugar kelp has had a long historical use in traditional diet patterns, including Blue Zones longevity diets, supporting its versatility and palatability within healthful, delicious eating patterns. It's important to note that sugar kelp does have a very high iodine content, which could be a potential innovation benefit (i.e., snack products with natural iodine sources, ingredients for formulation) for consumers seeking to increase iodine intake. Production standardization techniques to support consistent iodine levels, or processing methods (i.e., heat, soaking) that reduce iodine may be viable options. However, moderate use of kelp should be recommended as part of a healthy dietary pattern.
- **Functional Food Potential:** Sugar kelp contains significant amounts of dietary fiber and prebiotics, promoting digestive health and aiding in weight management. Sugar kelp is also rich in bioactive compounds such as fucoxanthin, phlorotannins, and fucoidans, which exhibit antioxidant, anti-inflammatory, and immunity-supporting benefits. These compounds also have antidiabetic properties, and may help support a healthy body weight, according to recent preliminary research. Given the significant potential of kelp production and application, further kelp research could represent an area of future research investment for the industry in order to better understand

the levels and mechanisms of action for these compounds.. Several ingredients have undergone this research-intensive transition in the past decades, such as probiotics, avocadoes, and mushrooms, in order to deepen understanding, shift public perception, influence the CPG landscape, and even shape public policy recommendations (i.e., peanuts influence on fat guidelines in the USDA Dietary Guidelines for Americans).

- **Food Safety Perspective**: Sugar kelp accumulates heavy metals at levels comparable to other varieties of kelp (though analysis has found lower levels of mercury in sugar kelp), however the relatively unpolluted waters of Alaska may enhance its safety and purity.
- **Culinary Versatility and Flavor Profile:** Its wide versatility in culinary applications—such as in salads, sushi, condiments and as a flavor enhancer—along with potential uses in biofuel production and as biostimulants for agriculture, further support its commercialization potential. Considering its nutritional benefits, bioactive compounds, food safety, and processing properties, sugar kelp emerges as a prime candidate for commercialization. It's important to note that sugar kelp does have a very high iodine content, so moderate use should be recommended. Future analysis of iodine and heavy metal content in Alaska-cultivated sugar kelp are essential to further understand these concerns.

However, if we were to select the most promising species solely from a nutritional standpoint, Ribbon and Sugar kelp would exhibit similar health properties and benefits based on the available data. Due to limited data availability, assessing the nutritional potential of Bull kelp is currently not feasible.

Part 5: Formats that Optimize Nutrient Benefits

Each processing format of Alaskan kelp offers unique advantages in terms of convenience, shelf life, and versatility, allowing consumers to enjoy the nutritional benefits of kelp in various ways. Below are considerations for popular formats of processing kelp.

Fresh

- Potential Advantages:
    - **Nutrient Density:** Fresh kelp retains all of its natural nutrients, providing maximum health benefits, including high levels of vitamins, minerals, bioactives and antioxidants.
    - **Local Market Appeal:** Promoting fresh kelp as a locally sourced, sustainable product can attract environmentally conscious consumers,

curious eaters (including those traveling to Alaska as tourists) and support local economies.

- Potential Drawbacks:
    - **Shorter Shelf Life:** Fresh kelp has a limited shelf life, requiring immediate consumption or preservation to avoid spoilage, which can lead to logistical challenges.
    - **Transportation and Storage:** Maintaining the freshness of kelp requires proper refrigeration during transportation and storage, increasing costs and environmental impact.
    - **Seasonal Availability:** Fresh kelp may only be available during certain times of the year, limiting its availability and consistency in the market.
    - **Increased Heavy Metal Exposure**: The bioavailability of heavy metals in fresh kelp can be higher than in some processed forms. Processing methods such as washing, boiling, or drying can reduce the heavy metal content, making the processed kelp safer for consumption (Nisizawa et al., 1987).

Pickled

- Potential Advantages:
    - **Nutrient retention**: Pickling involves minimal processing and can help preserve certain nutrients, such as fat-soluble vitamins and minerals. The acidic environment in pickling can even help enhance the bioavailability of certain minerals, making them easier for the body to absorb (Nishimura et al., 2000).
    - **Flavor enhancement**: Pickling can enhance the flavor of kelp, making it more palatable for some consumers.
- Potential Drawbacks
    - **High sodium content**: Pickled kelp often contains added salt, which may not be suitable for certain populations (i.e. individuals on a low-sodium diet.
    - **Potential nutrient losses**: Some water-soluble nutrients may leach into the pickling solution, resulting in minor nutrient losses.

Powdered

- Potential Advantages:
    - **Nutrient retention**: Powdered kelp (dried and finely ground) can help retain most nutrients as it involves minimal processing, especially if done at low temperatures, and includes the whole seaweed
    - **Versatility**: Powdered kelp can be conveniently packaged, and easily incorporated into various recipes and food products, allowing for diverse consumption options.
    - **Flavor:** The unique umami flavors of kelp may present culinary opportunities to use powdered kelp as a seasoning for recipe development and food formulation.

- Potential Drawbacks
    - **Potential nutrient losses**: Depending on the processing method, some heat-sensitive nutrients (vitamin A, for instance) may degrade during the grinding process.
    - **Shelf stability**: Powdered kelp may have a shorter shelf life compared to whole kelp, especially if not stored properly.

Freeze-dried

- Potential Advantages:
    - **Nutrient retention**: Freeze-drying preserves the nutritional content of kelp by removing moisture without significant heat exposure.
    - **Long shelf life**: Freeze-dried kelp has a longer shelf life compared to fresh or other processed forms, as moisture removal inhibits microbial growth.
- Potential Drawbacks
    - **Cost**: Freeze-drying can be an expensive process, which may increase the cost of the final product. However more product can be transported due to the reduction in weight.
    - **Energy-intensive**: Freeze-drying requires energy for freezing and sublimation, which may have environmental implications.

Dried

- Potential Advantages:
    - **Nutrient retention**: Drying kelp can help preserve its nutrients, especially if dried at low temperatures.
    - **Convenience**: Dried kelp is shelf-stable, easily packaged, and convenient for use in sushi rolls, salads, broths, or as a snack. It can also be easily rehydrated for use in many dishes.
- Potential Drawbacks
    - **Brittle texture**: Drying can result in a brittle texture, which may increase packaging to preserve the desired shape such as sheets of dried kelp and kombu.
    - **Potential nutrient losses**: Certain nutrients, such as water-soluble vitamins, may be lost during the drying process.

Each processing format has its own set of advantages and disadvantages as it relates to nutrient retention and losses. The choice of format depends on factors, such as consumer preferences, intended usage, and desired balance between convenience and nutritional value.

Literature Review Limitations

This literature review has several limitations, including most importantly, that there is a dearth of comparable, up to date food composition and food safety data on all

three species of kelp. Available data has been captured in this literature review, but all three species would benefit from a harmonized analysis of vitamins, minerals, bioactive compounds, and heavy metals.

Conclusion

This literature review reveals that each species of select kelp–*Alaria marginata* (ribbon kelp), *Nereocystis luetkeana* (bull kelp), and *Saccharina latissima* (sugar kelp)--offers unique health benefits when incorporated into the human diet. The relatively unpolluted Alaskan waters, however, enhance the safety and nutritional value of cultivated kelp, reducing the risk of contamination. To optimize the nutritional benefits, processing formats such as dried, powdered, and freeze-dried kelp are recommended, as they preserve nutrient content and offer convenience. Based on these considerations, *Saccharina latissima* (sugar kelp) seems to be most suitable for commercialization, leveraging its nutritional advantages and processing versatility to meet consumer demands and health needs.

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