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REVIEW OF THE LITERATURE ON THE SEAWEED INDUSTRY AND FOOD SAFETY ISSUES

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I. INTRODUCTION

The emerging seaweed aquaculture industry in the United States presents novel legal considerations, including how to regulate the sale of seaweed in its whole form as a food product to address potential food safety risks. There is currently no federal guidance on the food safety risks of seaweed in its whole form, leaving states unsure how to proceed with their own laws and regulations, impeding the growth of the industry.

In 2021, the National Sea Grant Law Center (NSGLC) hosted a virtual collaborative learning workshop for state regulators on seaweed food safety. Discussions during that workshop revealed that a primary barrier to the development of food safety regimes for seaweed aquaculture is a lack of knowledge among regulators and policy-makers about the potential hazards associated with seaweeds and seaweed products.[4] To begin to fill this knowledge gap, the NSGLC partnered with researchers at the University of Massachusetts Boston to conduct a literature review of the food safety hazards of seaweed production.

The objective of the literature review was to compile and index the primary, peer-reviewed literature related to seaweed food safety hazards. The review was focused on identifying literature on the potential contaminants of cultivated and wild collected seaweed, as well as potential regulatory, policy, and voluntary standards that address ways to minimize or control contamination. The literature survey is presented as a searchable web-based platform, where papers

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[4] The proceedings from the workshop are available at http://bit.ly/3UsyrQF.

are filterable by, among other criteria, geographic region, seaweed species, and food safety hazard.[5]

This report presents a summary of the findings of the literature review. To provide context to the food safety hazards of seaweed production, this report begins with an overview of the state of the industry both globally and in the United States. The report then discusses the food safety hazards identified in the literature which include chemical, microbial, physical, allergenic, and climate hazards. The report concludes with ideas regarding additional research needs.

II. GLOBAL INDUSTRY OVERVIEW: STATUS AND TREND

The seaweed industry is a vital global industry, which reached a total market value of USD 16.5 billion for cultivated species in 2020, with China, Indonesia, and the Republic of Korea the major exporters, and China, Japan, and the United States of America the leading importers.[6] The main production comes from aquaculture, which produced 35.1 million tonnes wet weight (ww), or about 97%, of the total 36 million tonnes produced in 2020.[7] Aquaculture production remains almost entirely marine macroalgae. Wild collection currently stands at ~0.9 million tonnes, which is about half its 1969 volume, when aquaculture and wild collection were equal halves of the total production.[8]

There has been a wide geographical disparity in seaweed aquaculture production with Asia being responsible for 99.5% of the global total, producing 34.9 million tonnes live weight in 2020.[9] This is a slight increase of 0.4 million tonnes over 2019's aquaculture production, when 99.1% of total production was through aquaculture and the remaining 0.9% through wild collection.[10] Similarly,

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[5] The database can be accessed through the Seaweed Hub website at https://seaweedhub.extension.uconn.edu/resources/peer-reviewed-journal-articles/.

[6] FOOD & AGRIC. ORG., THE STATE OF WORLD FISHERIES AND AQUACULTURE 2022 (2022) [hereinafter FAO], https://doi.org/10.4060/cc0461en.

[7] *Id.*

[8] Junning Cai et al., *Seaweeds and Microalgae: An Overview for Unlocking Their Potential in Global Aquaculture Development*, 1229 FAO FISHERIES AND AQUACULTURE CIRCULAR (2021), https://doi.org/10.4060/cb5670en.

[9] FAO, *supra* note 6.

[10] Cai et al., *supra* note 8.

in Oceania and Africa, a large portion (85.3% and 81.3% respectively in 2019) of their seaweed production comes from aquaculture, although these continents are minor contributors to world seaweed production, producing only 161.5 tonnes combined in 2019.[11] On the other hand, while the Americas and Europe were also minor contributors to global seaweed production in 2019 (487 tonnes for 1.4% share of world production and 287 tonnes for 0.8% share of world production respectively), their production was achieved mostly through wild collection (96.1% and 95.3% respectively).[12] Notably, a single country accounts for a majority of production in each of these last two regions. In the Americas, Chile produced 87.5% of the total, making it the 6th largest producing country globally at 426 tonnes wet weight. In Europe, Norway produced 163 tonnes wet weight, or 56.9% of the European total, making it the 9th largest producing country.[13]

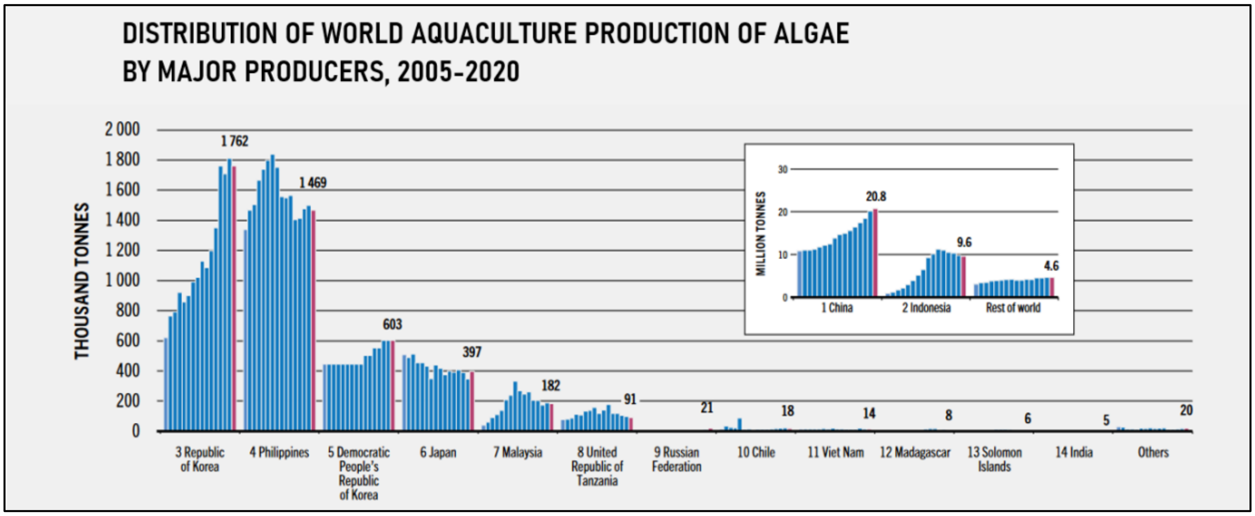

Figure 1: Production distribution of world aquaculture of algae by producing country in live weight[14]

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[11] *Id.*
[12] *Id.*
[13] *Id.*
[14] FAO, *supra* note 6. The FAO has made this figure available under the Creative Commons Attribution-NonCommercial-ShareAlike 3.0 IGO licence (CC BY-NC-SA 3.0 IGO; https://creativecommons.org/licenses/by-nc-sa/3.0/igo).

Seaweed is broadly classified into three taxonomic groups: brown seaweeds, also known as kelps, (around 2,000 species under *Phaeophyceae*), red seaweeds (over 7,200 species under *Rhodophyta*), and green seaweeds (more than 1,800 macroalgae species under *Chlorophyta*).[15] Cultivation of red seaweeds is primarily *Kappaphycus/Eucheuma*, *Gracilaria*, and *Porphyra* (nori), whilst brown seaweed is concentrated in growing kelp (*Laminaria/Saccharina*) and wakame (*Undaria*), which are cold water genera.[16] In 2020, the top 8 farmed species of seaweeds were either red or brown types and represented 93.7% of total global aquaculture production.[17] Japanese kelp *Laminaria japonica* alone accounted for 35.5% of the total, while the second and third most produced species were various red seaweeds from *Eucheuma* and *Gracilaria*, representing another 38% of the total combined.[18] Global seaweed cultivation market size is projected to reach up to US $30.2 billion by 2025, a substantial increase from current levels, and the North American market is expected to witness market growth of 11.2% in value during the forecast period of 2021-2027.[19]

Red seaweeds accounted for 52.6% in tonnes and 47.6% in value of global production as of 2019, recording a total of 18.3 million tonnes that year.[20] The annual percentage growth of red seaweed aquaculture was 10.3% between 1950 and 2019, which is higher than the global annual growth rate of seaweed aquaculture at 7.9%.[21] While red seaweed is taking the lead in terms of tonnage produced, brown seaweed cultivation is not far behind. As of 2019, brown seaweed cultivation accounted for 47.3% in tonnes and 52% in value of global production, experiencing an 10.9% annual growth rate in volume during the same time period.[22] Global production of green seaweed is very small and on a

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[15] Anushree Priyadarshini et al., *Economic Status of Seaweed: Production, Consumption, Commercial Applications, Hazards, and Legislations, in* 20 RECENT ADVANCES IN MICRO AND MACROALGAL PROCESSING: FOOD AND HEALTH PERSPECTIVES (Gaurav Rajauria & Yvonne V. Yuan eds., 2021), https://doi.org/10.1002/9781119542650.ch20.

[16] *Id.*

[17] FAO, *supra* note 6.

[18] *Id.*

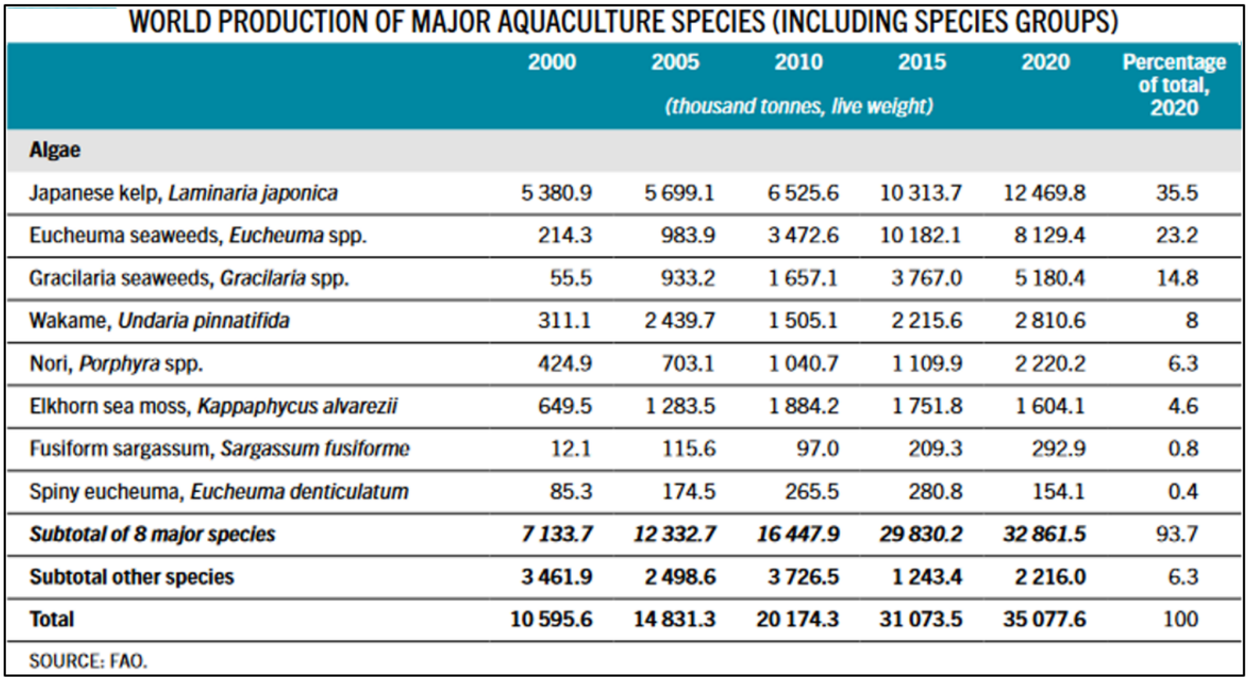
[19] MARKETSANDMARKETS, SEAWEED CULTIVATION MARKET SIZE, SHARE, TRENDS, AND FORECASTS TO 2025 (2020).

[20] Cai et al., *supra* note 8.

[21] *Id.*

[22] *Id.*

downward trend since the early 1990s. Only 16,698 tons were produced in 2019, which accounted for just 0.5% of all seaweed production by volume. Five species are primarily cultivated: *Caulerpa spp*; *Monostroma nitidum*; *Enteromorpha [Ulva] prolifera*; *Capsosiphon fulvescens*; and *Codium fragile.*[23]



WORLD PRODUCTION OF MAJOR AQUACULTURE SPECIES (INCLUDING SPECIES GROUPS)

	2000	2005	2010	2015	2020	Percentage of total, 2020
			(thousand tonnes, live weight)			
Algae						
Japanese kelp, *Laminaria japonica*	5 380.9	5 699.1	6 525.6	10 313.7	12 469.8	35.5
Eucheuma seaweeds, *Eucheuma* spp.	214.3	983.9	3 472.6	10 182.1	8 129.4	23.2
Gracilaria seaweeds, *Gracilaria* spp.	55.5	933.2	1 657.1	3 767.0	5 180.4	14.8
Wakame, *Undaria pinnatifida*	311.1	2 439.7	1 505.1	2 215.6	2 810.6	8
Nori, *Porphyra* spp.	424.9	703.1	1 040.7	1 109.9	2 220.2	6.3
Elkhorn sea moss, *Kappaphycus alvarezii*	649.5	1 283.5	1 884.2	1 751.8	1 604.1	4.6
Fusiform sargassum, *Sargassum fusiforme*	12.1	115.6	97.0	209.3	292.9	0.8
Spiny eucheuma, *Eucheuma denticulatum*	85.3	174.5	265.5	280.8	154.1	0.4
Subtotal of 8 major species	***7 133.7***	***12 332.7***	***16 447.9***	***29 830.2***	***32 861.5***	93.7
Subtotal other species	**3 461.9**	**2 498.6**	**3 726.5**	**1 243.4**	**2 216.0**	6.3
Total	**10 595.6**	**14 831.3**	**20 174.3**	**31 073.5**	**35 077.6**	100

SOURCE: FAO.

Figure 2: Top 8 aquaculture species for seaweeds in live weight, 2000-2020[24]

All three types of seaweed are very beneficial, especially as human food and animal feed.[25] While some seaweeds are consumed whole, most are processed into a variety of products - e.g., fresh, dried, extracted liquids, canned, flaked, powdered, or salted.[26] Seaweed products are commonly used in soups, salads,

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[23] *Id.*

[24] FAO, *supra* note 6. The FAO has made this figure available under the Creative Commons Attribution-NonCommercial-ShareAlike 3.0 IGO licence (CC BY-NC-SA 3.0 IGO; https://creativecommons.org/licenses/by-nc-sa/3.0/igo).

[25] Priyadarshini et al., *supra* note 15.

[26] Alejandro H. Buschmann et al., *Seaweed Production: Overview of the Global State of Exploitation, Farming and Emerging Research Activity*, 52:4 EUR. J. PHYCOLOGY 391 (2017), https://doi.org/10.1080/09670262.2017.1365175.

sushi, and snacks, as well as thickening agents.[27] Seaweed is also commonly found in dietary supplements due to their nutritious bioactive compounds and micronutrients.[28] For example, *Palmaria palmata* and *Porphyra tenera* are extremely rich sources of protein.[29] Brown seaweeds provide vital bioactive compounds that can promote overall good health. Research suggests that brown seaweed helps to control sugar levels and minimizes risk of obesity and high cholesterol, is rich in antioxidants, and helps to build a strong immune system.[30] Seaweed is also used for medicines, fertilizers, biofuels, and cosmetics, amongst other uses.[31]

Research indicates seaweed aquaculture has numerous environmental benefits. Seaweed production does not have to compete for fresh water, agricultural land, or fertilizer inputs and does not threaten the commons for other extractive resource uses.[32] Seaweed production also has a relatively low carbon footprint.[33] Seaweed requires no inputs to grow, other than sunlight and marine nutrients; it absorbs carbon dioxide efficiently from its environment and pulls more greenhouse gas from water than eelgrass, mangroves, and salt marshes combined based on biomass; and it may help in mitigating methane emissions when used as a feed supplement in cattle farming.[34] Seaweed aquaculture also has

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[27] Cai et al., *supra* note 8; Priyadarshini et al., *supra* note 15.

[28] Cai et al., *supra* note 8.

[29] Mona M. Ismail et al., *Therapeutic Uses of Red Macroalgae*, 25 MOLECULES 4411 (2020), https://doi.org/10.3390/molecules25194411.

[30] Paul Cherry et al., *Risks and Benefits of Consuming Edible Seaweeds*, 77:5 NUTRITION REV. 307 (2019), https://doi.org/10.1093/nutrit/nuy066; Fatima Ferdouse et al., *The Global Status of Seaweed Production, Trade and Utilization*, 124 FAO GLOBEFISH RSCH. PROGRAMME 1 (2018), https://policycommons.net/artifacts/2242866/the-global-status-of-seaweed-production-trade-and-utilization/3000967/; Ismail et al., supra note 29.

[31] Buschmann et al., *supra* note 26.

[32] *Unlocking Kelp's Potential as a Major Biofuel Source*, SCIENCEDAILY (March 2, 2021), https://www.sciencedaily.com/releases/2021/03/210302094053.htm#:~:text=Summary%3A,biofuel%20harvested%20from%20the%20ocean.

[33] Cai et al., *supra* note 8; Priyadarshini et al., *supra* note 15.

[34] *Seaweed Aquaculture: Seaweed Farming, the Fastest-Growing Aquaculture Sector, can Benefit Farmers, Communities, and the Environment*, NOAA FISHERIES (Sept. 28, 2020) [hereinafter NOAA], https://www.fisheries.noaa.gov/national/aquaculture/seaweed-aquaculture; Breanna M. Roque et al., *Red Seaweed* (Asparagopsis taxiformis) *Supplementation Reduces Enteric Methane by Over 80 Percent in Beef Steers*, 16 PLOS ONE 1 (2021), https://doi.org/10.1371/journal.pone.0247820.

promising potential as a bioremediation technology for removing nutrients such as nitrogen and phosphorus, which are major factors driving algal blooms that deplete oxygen in oceans and can kill aquatic animals.[35] Seaweed also provides new habitats for fish, helps to maintain good water quality through absorption of micronutrients, and supports coastal areas to minimize the effects of wave energy.[36] Seaweed is also a potentially great source of renewable energy from biofuel and a more sustainable raw material compared to other sources of biofuels.[37]

While there is a concern that seaweed grown on lines may potentially entangle large marine animals (e.g., whales, turtles),[38] current systems are looking at using tensioned lines to minimize the possibility of entanglement.[39] Current research is also focused on real-time reporting for weak links that can indicate entanglement or system stress in poor weather.[40]

III. OVERVIEW OF THE U.S. SEAWEED MARKET

The U.S. seaweed industry has received a lot of attention in recent years and is acknowledged as a very important industry from an economic, social, and environmental standpoint. As of 2019, the U.S. was producing 3,394 tonnes wet weight of edible seaweed, with the majority of production coming from

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[35] NOAA, *supra* note 34; Priyadarshini et al., *supra* note 15.

[36] Seth J. Theuerkauf et al., *Habitat Value of Bivalve Shellfish and Seaweed Aquaculture for Fish and Invertebrates: Pathways, Synthesis and Next Steps*, 14 REVS. AQUACULTURE 54 (2021), https://doi.org/10.1111/raq.12584; Priyadarshini et al., *supra* note 15.

[37] ScienceDaily, *supra* note 32.

[38] Iona Campbell et al., *The Environmental Risks Associated with the Development of Seaweed Farming in Europe – Prioritizing Key Knowledge Gaps*, 6 FRONTIERS IN MARINE SCI. 107 (2019), https://doi.org/10.3389/fmars.2019.00107.

[39] Gretchen E. Bath et al., *A Global Review of Protected Species Interactions with marine Aquaculture*, 15 REVIEWS IN AQUACULTURE 1686 (2023), https://doi.org/10.1111/raq.12811.

[40] Press Release, Atlantic States Marine Fisheries Commission, ASMFC Awards Grants to Four Aquaculture Pilot Projects (Sept. 16, 2020), http://www.asmfc.org/uploads/file/5f625636pr20_AquaculturePilotProjectsSelected.pdf.

aquaculture.[41] Seaweeds in the U.S. are mostly harvested for food uses, with a small part being used as fertilizer, in medicine, and for other industrial uses.[42]

In the past, eleven species were produced: dulse (*Palmaria palmata*); sugar kelp (*Saccharina latissima*); horsetail kelp or *digitata* (*Laminaria digitata*); *alaria* or winged kelp (*Alaria esculenta*); rockweed or knotted wrack (*Ascophyllum nodosum*); bladderwrack (*Fucus vesiculosus*); sea lettuce (*Ulva lactuca*); laver (*Porphyra umbillicalis*); Irish sea moss (*Chondrus crispus*); and worm weed (*Ascophyllum nodosum)*. Recently, the most harvested species are sugar kelp, dulse, *alaria*, laver, and Irish moss.[43]

Growers in the U.S are exploring integrating the culturing of seaweed, alongside fish and mollusk culture. This integrated multi-trophic aquaculture (IMTA) system is proven to increase both economic and environmental sustainability, as the waste from one aquatic species serves as fertilizer and food for another, thereby lessening the environmental impacts associated with aquaculture production while increasing the diversity of crops produced.[44]

The majority of commercial production takes place in New England, the Pacific Northwest, and Alaska.[45] The states of Alaska and Maine are the most significant producing states in the U.S. market and have the highest growth potential for seaweed development, accounting for more than 85% of total edible

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[41] Cai et al., *supra* note 5.

[42] NOAA, *supra* note 32; PETER PICONI ET AL., ISLAND INSTITUTE, EDIBLE SEAWEED MARKET ANALYSIS (2020), https://oceansalaska.org/wp-content/uploads/2021/06/Edible-Seaweed-Market-Analysis-1.17.20.pdf.

[43] PICONI ET AL., *supra* note 42.

[44] *See Integrated Multi-Trophic Aquaculture*, SCIENCEDIRECT, https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/integrated-multi-trophic-aquaculture (last visited Dec. 5, 2023). *See also Integrated Multi-Trophic Aquaculture (IMTA)*, GULF STATE MARINE FISHERIES COMM'N, https://www.gsmfc.org/aquaculture_imta (last visited Dec. 5, 2023).

[45] *Seaweed Farming, the Fastest-Growing Aquaculture Sector, can Benefit Farmers, Communities, and the Environment*, NOAA FISHERIES, https://www.fisheries.noaa.gov/national/aquaculture/seaweed-aquaculture (last visited Dec. 1, 2023); PICONI ET AL., *supra* note 42.

seaweed production in the U.S.[46] The development of seaweed aquaculture in these states has focused mainly on cultivation of several species of kelps, including *Macrocystis pyrifera, Saccharina latissimi, and Alaria marginata*,[47] with a significant amount of interest in bull kelp (*Nereocystis luetkeana*) in Alaska.

In 2019, Alaska seaweed aquaculture farmers harvested over 136,000 pounds (61.7 tonnes) of seaweed, including sugar, ribbon and bull kelps, doubling the state's first commercial harvest in 2017. In 2022, that number again increased dramatically to over 872,000 pounds (395.5 tonnes).[48]

The U.S has the second largest coastline (95,000 miles) in the world, and it is very suitable for seaweed farming.[49] In fact, the large coastlines of both Alaska and Maine are still largely untapped when it comes to seaweed production. The U.S. could become a leading producer of seaweed in the world, if resources are maximized sustainably.[50] Currently, seaweed production is limited by a short growing and harvest season (winter and spring), although this does have a seasonal alignment with the primary fisheries' shoulder seasons, when fishermen are not as busy harvesting groundfish, lobsters, or shellfish.[51] Processing infrastructure is also limited to a small set of processors, who often also sell seed spools. Harvesters who do not have contracts with them usually have little or no

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[46] Jangkyun Kim et al., *Opportunities, Challenges and Future Directions of Open-Water Seaweed Aquaculture in the United States*, 58:5 PHYCOLOGIA 446 (2019), https://doi.org/10.1080/00318884.2019.1625611; PICONI ET AL., *supra* note 42.

[47] Michael S. Stekoll et al., *Mariculture Research of* Macrocystis pyrifera *and* Saccharina Iatissima *in Southeast Alaska*, 52 J. WORLD AQUACULTURE SOC'Y 1031 (2021), https://doi.org/10.1111/jwas.12765; ALASKA SEA GRANT, RESULTS- POST-CONFERENCE SURVEY FOR THE 2023 MARICULTURE CONFERENCE OF ALASKA (2023), https://alaskaseagrant.org/wp-content/uploads/2023/04/2023-Mariculture-Conf-Survey-results.pdf.

[48] *Aquatic Farming- Aquatic Plants Production Data*, ALASKA DEPT. OF FISH & WILDLIFE, https://www.adfg.alaska.gov/index.cfm?adfg=fishingaquaticfarming.aquaticfarminfo_aquaticplants (last visited Dec. 1, 2023).

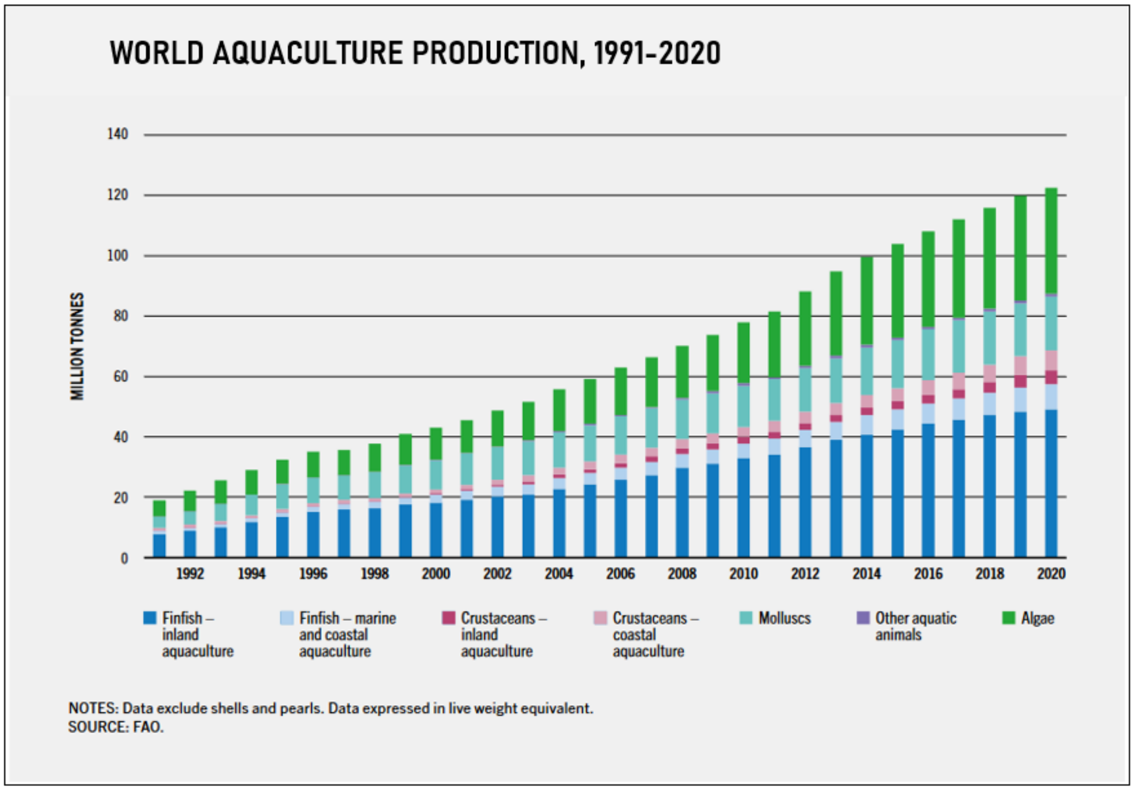
[49] *How Long is the U.S. Shoreline?*, NAT'L OCEAN SERV. (Aug. 8, 2023), https://oceanservice.noaa.gov/facts/shorelength.html#:~:text=NOAA's%20official%20value%20for%20the,U.S.%20shoreline%20is%2095%2C471%20miles.

[50] Alexandra Talty, '*It's a Miracle Crop': The Pioneers Pushing the Powers of Seaweed*, THE GUARDIAN (Aug. 26, 2021), https://www.theguardian.com/environment/2021/aug/26/new-york-seaweed-farming-kelp-producers.

[51] PICONI ET AL., *supra* note 42.

access to seeds. Access to seed supply could be increased if others, such as shellfish hatcheries, became more involved in providing seed. These limiting factors have led to a substantial amount of imported seaweeds from countries with more well-developed seaweed industries.

Growth of the U.S. seaweed industry for food is projected to grow based on increasing harvesting and processing capacity. This growth could be maximized if the constraints that are keeping the seaweed industry are addressed- for instance, increasing manpower, farming and processing infrastructure, and market demand for location production and developing more effective scalable products.


WORLD AQUACULTURE PRODUCTION, 1991-2020

NOTES: Data exclude shells and pearls. Data expressed in live weight equivalent.
SOURCE: FAO.

Figure 4: World Aquaculture Production 1991-2020 in live weight[52]

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[52] FAO, *supra* note 6. The FAO has made this figure available under the Creative Commons Attribution-NonCommercial-ShareAlike 3.0 IGO licence (CC BY-NC-SA 3.0 IGO; https://creativecommons.org/licenses/by-nc-sa/3.0/igo).

IV. OVERVIEW OF THE FOOD SAFETY HAZARDS OF EDIBLE SEAWEED

U.S. seaweed cultivation has the potential to become an incredibly vigorous sector that can generate massive benefits.[53] Human consumption of seaweed is growing steadily, more than the other uses.[54] The versatility and variety of many seaweeds suggest that they can be used in a broad range of food products, adding healthy, low calorie, nutrient dense opportunities for food manufacturers and distributors.[55] Seaweed aquaculture for human food is projected to drive the growth of the industry as numerous efforts are in place to expand harvest and processing capacity by developing infrastructure to meet the growing demands.[56]

However, consuming seaweed may present food safety hazards. Seaweed may encounter several hazards during its journey through production and the supply chain. Food safety hazards refer to substances or agents that can cause harm or health problems for people who consume them. These can happen when the food is exposed to substances that are hazardous, which acts as a contaminant to the food.

Studies have identified contaminants, such as arsenic, cadmium, lead, mercury, and *Salmonella,* as major hazards in edible seaweed species and microalgae; with brown seaweed species having the highest concentration of contaminants.[57] Studies have also noted the following as emerging hazards,

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[53] PICONI ET AL., *supra* note 42.

[54] J.L. Banach et al., *Food Safety Hazards in the European Seaweed Chain*, 19:2 COMPREHENSIVE REV. FOOD SCI. AND FOOD SAFETY 332 (2020), https://doi.org/10.1111/1541-4337.12523; Ferdouse et al., supra note 30; PICONI ET AL., *supra* note 42.

[55] Buschmann et al., *supra* note 26.

[56] PICONI ET AL., *supra* note 42.

[57] Concepción Almela et al., *Heavy Metal, Total Arsenic, and Inorganic Arsenic Contents of Algae Food Products*, 50 J. AGRIC. FOOD CHEM. 918 (2002), https://doi.org/10.1021/jf0110250; Banach et al., *supra* note 54; Maria Bouga & Emilie Combet, *Emergence of Seaweed and Seaweed-Containing Foods in the UK: Focus on Labeling, Iodine Content, Toxicity and Nutrition*, 4 FOODS 240 (2015), https://doi.org/10.3390/foods4020240; Qing Chen et al., *Distribution of Metals and Metalloids in Dried Seaweeds and Health Risk to Population in Southeastern China*, 8 SCI. REP. 3578 (2018), https://doi.org/10.1038/s41598-018-21732-z; J.L. Banach et al., *Food Safety During*

though with limited data: allergens, polycyclic aromatic hydrocarbons, toxic metabolites, pesticide residues, dioxins and polychlorinated biphenyls, brominated flame retardants, pharmaceuticals, marine biotoxins, macro- and microplastics, other pathogenic bacteria, rare earth elements, norovirus, and hepatitis E virus.[58]

Consuming certain seaweed species may expose individuals to certain food safety hazards, such as heavy metals and microcystin contamination, and health challenges from excessive consumption of certain elements, such as iodine.[59] For example, inorganic arsenic (iAs) has the capacity to induce cancer in human and other living tissues.[60] Young children, frail or elderly people, and others with weakened immune systems are the most susceptible to hazards and exposure can be fatal for these populations.[61] Exposure to food-borne contaminants can also lead to severe illness, such as endocarditis, arterial infections, and arthritis.[62]

Poor sewage systems increase the accumulation of heavy metals in seaweed, but most areas contain levels that pose minimal health risks.[63] Other factors that may contribute to seaweed food safety include, but are not limited to, location of the cultivation sites (sites adjacent to legacy coal fired power plants have greater heavy metal contamination), the strain of the species of seaweed,

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Seaweed Cultivation at Offshore Wind Fars: An Exploratory Study in the North Sea, 120 MARINE POLICY (2020), https://doi.org/10.1016/j.marpol.2020.104082; M. Caliceti et al., *Heavy Metal Contamination in the Seaweeds of the Venice Lagoon*, 47:4 CHEMOSPHERE 443 (2002), https://doi.org/10.1016/s0045-6535(01)00292-2.

[58] Banach et al., *supra* note 54.

[59] Bouga & Combet, *supra* note 57.

[60] Francesco Cubadda et al., *Human Exposure to Dietary Inorganic Arsenic and Other Arsenic Species: State of Knowledge, Gaps, and Uncertainties*, 579 SCI. TOTAL ENV'T 1228 (2017), https://doi.org/10.1016/j.scitotenv.2016.11.108.

[61] Coral Beach, *Seaweed Farm Linked to Salmonella Outbreak Recalls Products*, FOOD SAFETY NEWS (Nov. 15, 2016), https://www.foodsafetynews.com/2016/11/seaweed-farm-linked-to-salmonella-outbreak-recalls-products/.

[62] *Id.*

[63] Cherry et al., *supra* note 30.

seasonal variation and climate change, handling, method of harvest and post-harvest management, and processing methods.[64]

Analysis from Spanish seaweed samples have shown that cadmium and inorganic arsenic are higher than legally permissible in other countries.[65] The U.S. has not established food safety limits for most seaweed food products, but standards do exist for certain seaweeds when used as a food additive. FDA has recently stated that seaweed will be treated as a raw agricultural commodity in its whole form,[66] and therefore regulated under the Federal Food Drug and Cosmetic Act and the Food Modernization and Safety Act and its Current Good Manufacturing Practice, Hazard Analysis, and Risk-Based Preventive Controls for Human Food Rule.[67]

V. LITERATURE REVIEW FINDINGS

To summarize the findings from this literature review, seaweed hazards are grouped into five categories: chemical, microbiological, physical, allergenic, and climatic.

A. Chemical Hazards

Chemical hazards are non-biological toxic substances known to negatively impact human health in a variety of ways. These impacts include, but are not limited to, irritation and sensitivity at a minimum and carcinogenicity at a

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[64] Banach et al., *supra* note 54; Y.O. Hwang et al., *Total Arsenic, Mercury, Lead, and Cadmium Contents in Edible Dried Seaweed in Korea*, 3:1 FOOD ADDITIVES & CONTAMINANTS: PART B SURVEILLANCE 7 (2010), https://doi.org/10.1080/19440040903532079; Janet Kübler et al., *Climate Change Challenges and Opportunities for Seaweed Aquaculture in California, the United States*, 52 J. WORLD AQUACULTURE SOC'Y 1069 (2021), https://doi.org/10.1111/jwas.12794; Deborah Smith, *Invading Fish Threat to Kelp Forests*, UNSW SYDNEY (Jan. 16, 2017), https://newsroom.unsw.edu.au/news/science-tech/invading-fish-threat-kelp-forests.

[65] Almela et al., *supra* note 57; Concepción Almela et al., *Total Arsenic, Inorganic Arsenic, Lead and Cadmium Contents in Edible Seaweed Sold in Spain*, 44:11 FOOD & CHEM. TOXICOLOGY 1901 (2006), https://doi.org/10.1016/j.fct.2006.06.011; Cubadda et al., *supra* note 60.

[66] Catherine M. Janasie, *Federal Food Safety Framework: Where does Seaweed Fit In?*, 18:2 J. FOOD LAW & POL'Y 74, 77 (2022), https://scholarworks.uark.edu/cgi/viewcontent.cgi?article=1320&context=jflp.

[67] 21 C.F.R. § 117.

maximum.[68] Chemical hazards can also be introduced through processing due to reactions between naturally occurring compounds in seaweed and additives, ingredients, or packaging materials, e.g., acrylamide, ethyl a carbamate, and furan.[69]

Chemical hazards summarized below include: (1) heavy metals, minor element, and rare earth elements; (2) Iodine; (3) Polycyclic Aromatic Hydrocarbons (PAHs); (4) Micro- and Nanoplastics; (5) Agrochemicals; (6) Pharmaceutical and Personal Care Products; (7) Marine Biotoxins; and (8) Persistent Organic Pollutants (POPs).

As discussed in more detail below, some seaweed species or products may exceed recommended intake levels of heavy metals and other contaminants. Existing regulations vary substantially by country and noticeably, are completely absent in Canada and the United States (except for when some seaweeds are used as an additive). The European Union (EU) has codified some maximum residue limits (MRLs). Some countries such as France, as shown in Figure 5, have also set their own recommended or legal maximums, which may or may not be as stringent. China, the world's largest seaweed producer, has some of the stricter limits for arsenic, lead, and cadmium.

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[68] U.S. Dep't of Lab., *Chemical Hazards and Toxic Substances*, OCCUPATIONAL SAFETY AND HEALTH ADMIN, https://www.osha.gov/chemical-hazards (last visited Dec. 1, 2023).

[69] Health Canada, *Chapter 4: Food Safety Hazards, in* IMPORTED & MANUFACTURED FOOD PROGRAM INSPECTION MANUAL (Archived), CANADA FOOD INSPECTION AGENCY (2022).

Element	**Max Recommended Level (mg.kg-1 dry matter (DM))**
Inorganic Arsenic	3
Cadmium	0.5
Mercury	0.1
Lead	5
Tin	5
Iodine	2000

Figure 5: Maximum values for trace elements and iodine in seaweed used as a vegetable or condiment recommended by the Conseil Supérieur d'Hygiène Publique de France (CSHPF).[70]

i. Heavy Metals

Heavy metals are a high-density group of metallic chemical elements that are very toxic and can negatively affect people's health, even at a low concentration**.** The most known heavy metals in edible seaweeds are arsenic (As), cadmium (Cd), lead (Pb), and mercury (Hg), each of which are discussed below. Chromium (Cr) and Thallium (Tl) are additional potential heavy metals of concern. Several researchers have shown that seaweed species easily bioaccumulate heavy metals at a very low level.[71] However, the level at which the species becomes contaminated primarily depends on the chemical composition of the specific species.[72]

Generally, all seaweeds are up to 70-90% water in its whole fresh form, but the levels of polysaccharides, which easily bind to metals, differ between brown, red, and green macroalgae.[73] In addition, brown seaweeds are made up of

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[70] ANSES, OPINION OF THE FRENCH AGENCY FOR FOOD, ENVIRONMENTAL AND OCCUPATIONAL HEALTH & SAFETY ON "MAXIMUM CADMIUM LEVELS FOR SEAWEED INTENDED FOR HUMAN CONSUMPTION" (2020), https://www.anses.fr/en/system/files/ERCA2017SA0070EN.pdf.

[71] Almela et al., *supra* note 65; Chen et al., *supra* note 55; P. Karthick et al., *Ecological Implications of Trace Metals in Seaweeds: Bio-Indication Potential for Metal Contamination in Wandoor, South Andaman Island*, 38:4 THE EGYPTIAN J. AQUATIC RSCH. 227 (2012), https://doi.org/10.1016/j.ejar.2013.01.006.

[72] ANSES, *supra* note 69.

[73] *Id.*

a great amount of alginate, which is also known to work as a binder.[74] This increases the chances of the seaweed trapping heavy metals, leading to the high concentrations seen in brown seaweed species. As a result, the concentrations of inorganic metals, especially arsenic, found in edible brown seaweed species are usually very high compared to red and green seaweed species, and its consumption may exceed three times the World Health Organization (WHO) tolerable daily intake levels.[75] For example, one study found consuming 3 grams per day of the *Hizikia fusiform* samples could represent up to 15% of the WHO arsenic and cadmium tolerable daily intake levels[76]

The concentration of heavy metals in seaweed varies amongst species, growing area, season, seaweed growth rates, and within species, from one part of the seaweed to another.[77] For instance, the part of the seaweed that is exposed or in contact with the production water tends to absorb more contaminants compared to parts that do not have direct contact with water. Environmental characteristics, such as temperature, salinity, location, and sunlight also have an impact on the level of contamination.[78] The contaminant exposure is seen more in perennial seaweeds, and regular consumption may lead to toxicity of heavy metals in humans.[79] Another study in Korea measured 426 dried seaweed products for heavy metals (arsenic, lead, mercury, and cadmium) and discovered that daily consumption of 8.5 g dry weight of the seaweed product resulted in consumption of between 0.2% to 6.7% of tolerable weekly intake of these metals.[80]

a. Arsenic (As)

Arsenic is a naturally occurring metal found in groundwater, sediments, and soil. It can be introduced into the marine environment through natural causes

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[74] NAT'L INST. OF NUTRITION & SEAFOOD RSCH., POTENTIAL RISKS POSED BY MACROALGAE FOR APPLICATION AS FEED AND FOOD – A NORWEGIAN PERSPECTIVE (2016).

[75] Almela et al., *supra* note 65.

[76] *Id.*

[77] ANSES, *supra* note 69.

[78] NAT'L INST. OF NUTRITION AND SEAFOOD RSCH., *supra* note 73.

[79] Joanna Burger et al., *Lead (Pb) in Biota and Perceptions of Pb Exposure at a Recently Designated Superfund Beach Site in New Jersey*, 75:5 J. TOXICOLOGY AND ENV'T HEALTH, PART A 272 (2012), https://doi.org/10.1080/15287394.2012.652058.

[80] Hwang et al., *supra* note 64.

such as rock weathering and geothermal activity, as well as by industrial emissions, fertilizers, and pesticides. Arsenic in seaweeds is classified into three categories: toxic or inorganic arsenic (class 1 carcinogens), nontoxic (arsenobetaine), and potentially toxic (fat-soluble arsenic, arsenosugars, and other organoarsenicals).[81] However, most arsenic found in seaweed species are predominantly arsenosugars, which are potentially toxic and have been reported to resist cooking and digestion processes. Rather, they directly enter the hepatic portal system, which is the venous system that returns blood from the digestive tract and spleen to the liver.[82] There are considerable differences between individuals in the excretion rate of arsenosugars, which can range from 4% up to 95%. This high variability of arsenosugar metabolism means the toxicity of arsenosugars can also vary depending on the individual. Thus, it is difficult to generalize about the safety or hazards of consuming arsenosugar rich foods without characterizing the metabolic fate of arsenosugars in the body.[83] When arsenosugars are metabolized, they break down into at least twelve different metabolites, the toxicities of which are also unknown.

Seaweed species can accumulate arsenic up to 50,000 times higher than the arsenic content in the surrounding water.[84] Brown seaweeds have been found to accumulate the highest concentrations of arsenic, followed by red seaweed and green seaweed respectively.[85] Food products made from hijiki (a brown seaweed) have the highest amount of total arsenic.[86] Rose et al. documented hijiki species with inorganic arsenic concentration ranging from 67-96 mg/kg, significantly above the hazard level specified in the EU limit of 3 mg/kg.[87] Other seaweed species investigated were all found to have inorganic arsenic concentration levels that are less than 0.3 mg/kg, which were considered as minor hazards. A

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[81] Cherry et al., *supra* note 30.

[82] *Id.*

[83] *Id.*

[84] FOOD & AGRIC. ORG., THINKING ABOUT THE FUTURE OF FOOD SAFETY – A FORESIGHT REPORT (2022), https://doi.org/10.4060/cb8667en.

[85] Zengling Ma et al., *Total and Inorganic Arsenic Contents in Seaweeds: Absorption, Accumulation, Transformation and Toxicity*, 497 AQUACULTURE 49 (2018), https://doi.org/10.1016/j.aquaculture.2018.07.040.

[86] FOOD & AGRIC. ORG., *supra* note 83.

[87] Martin Rose et al., *Arsenic in Seaweed – Forms, Concentration and Dietary Exposure,* 45:7 FOOD & CHEMICAL TOXICOLOGY 1263 (2007), https://doi.org/10.1016/j.fct.2007.01.007.

significant amount of total inorganic arsenic could be removed from seaweed through thorough washing, soaking, cooking, boiling, heating, processing, and treating with sodium chloride.[88]

b. Cadmium (Cd)

Cadmium is a heavy metal naturally found in soil, rock, coal, and mineral fertilizer, and when mined, can escape into the environment (e.g., air, water). Cadmium contamination in seaweed happens through natural processes and from anthropogenic activities.[89] Reports have noted seaweed as having very high cadmium concentrations compared to other types of food.[90] Reports also found cadmium in edible seaweeds ranges from below detection limits of 0.001 µg/mL, up to 9.8 mg/kg dry weight (dw).[91]

The most influential factors in the accumulation rate of cadmium in seaweeds are the strain of species and seasonal variation. In one study, brown seaweeds were recorded as having the highest cadmium concentration rate in general,[92] and mean cadmium concentrations were reported as 0.10 ± 0.06 mg/kg dw (brown seaweed, $n = 22$) and 0.30 ± 0.34 mg/kg dw for red seaweed ($n = 18$).[93] However, seasonal variation plays a role in concentration levels. Red seaweed species are reported to accumulate more cadmium in winter, compared to brown and green species.[94] The accumulation of cadmium metal differs from one species to another. For example, at a consumption rate of 3.3 to 12.5 grams/day, *Laminaria digitata* contains .024 to.0 90 mg of cadmium, which

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[88] Banach et al., *supra* note 57.
[89] Banach et al., *supra* note 54.
[90] M. Sá Monteiro, *Analysis and Risk Assessment of Seaweed*, 17:S2 EFSA J. (2019), https://doi.org/10.2903/j.efsa.2019.e170915.
[91] Banach et al., *supra* note 54.
[92] *Id.*; Victoria Besada et al., *Heavy Metals in Edible Seaweeds Commercialised for Human Consumption*, 75 J. MARINE SYS. 305 (2009), https://doi.org/10.1016/j.jmarsys.2008.10.010; Donatella Desideri et al., *Essential and Toxic Elements in Seaweeds for Human Consumption*, 79:3 J. TOXICOLOGY AND ENV'T HEALTH, PART A 112 (2016), https://doi.org/10.1080/15287394.2015.1113598..
[93] Banach et al., *supra* note 54.
[94] Adriana A. Pérez et al., *Levels of Essential and Toxic Elements in* Porphyra Columbina *and* Ulva *sp. from San Jorge Gulf, Patagonia Argentina*, 376 SCIENCE TOTAL ENV'T 51 (2007), https://doi.org/10.1016/j.scitotenv.2006.11.013.

corresponds to 40% to 150% of the tolerable daily intake, while *Laminaria japonica* contains 0.45 to 0.80 mg/kg, which exceeds the maximum limits for seaweed products according to legislation in France (0.5 mg/kg of dw) and Australia/New Zealand (0.2 mg/kg of dw).[95]

c. Lead (Pb)

Lead is a heavy metal found mostly in paints and petrol. The geographical location of the seaweed plays an important role in the accumulation rate of lead.[96] Higher lead concentrations are reported in locations with high anthropogenic activities, although the range, from <0.05 mg/kg (limit detection) dw to 2.44 mg/kg, is considered a low-risk hazard.[97] Lead contamination can also happen throughout the supply chain (transporting, processing, handling, and packaging), but accumulation occurs at a lower rate.

Several studies recorded different species to have accumulated a higher lead concentration than others. Brown seaweed (*U. pinnatifida*) was noted for a higher bioaccumulation of lead of several edible seaweed products investigated.[98] Green seaweed (*Ulva lactuca*) accumulates more lead in summer, followed by red seaweed (*Pyropia columbina*) due to seasonal variation.[99] The increase in temperature during summer months is reported to cause an increase in metabolic activities, which makes the intake of lead higher.

d. Mercury (Hg)

Mercury is a heavy metal that can occur naturally and through anthropogenic activities.[100] As they grow, seaweeds can uptake mercury from the environment in its methylmercury form, its most toxic form. The concentration level of mercury varies among the species type and location of cultivation. Brown

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[95] Cherry et al., *supra* note 30.
[96] Chen et al., *supra* note 57.
[97] Almela et al., *supra* note 66.
[98] *Id.*
[99] Desideri et al., *supra* note 91.
[100] Banach et al., *supra* note 54.

seaweed species, such as *U. pinnatifida* and *Sargassum fusiforme,* are found to have the highest mercury accumulations.[101] Mercury concentrations are usually around 0.001 to 0.050 mg/kg dry weight, with average of 0.011 mg/kg. These levels exceed the EU MRL for mercury of 0.01 mg/kg for pesticide residues on food products, including algae.[102] Geographical differences play an important role in the accumulation rate of mercury in seaweeds.[103]

e. Minor and Rare Earth Elements

Minor elements are elements generally found in trace amounts in seaweeds. Minor elements can either be essential (needed in the growth process) or non-essential (toxic metals). Rare earth elements on the other hand are metallic elements that are similar in nature, mostly occur together, and are difficult to separate from one another, including cerium, lanthanum, neodymium, yttrium, and scandium. These elements are classified as potential hazards when consumed.[104] The major factors affecting accumulation rate of these hazards include, but are not limited to, geographic area, season, species type, and taxonomic genus.[105]

ii. Iodine (I)

Iodine is an essential mineral that is only supplied through diet and is needed in the human body to make thyroid hormones that help in growth, development, and regulation of normal metabolism.[106] Iodine is found in food and water and can be soluble (iodide) or less soluble (iodate). However, while iodine

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[101] *Id.*

[102] Hwang et al., *supra* note 64. The relevant EU regulation is Reg. (EU) 2018/73.

[103] Chen et al., *supra* note 57.

[104] Banach et al., *supra* note 54.

[105] Chen et al., *supra* note 57; Ote Miedico et al., *Characterisation and Chemometric Evaluation of 21 Trace Elements in Three Edible Seaweed Species Imported from South-East Asia*, 64 J. FOOD COMPOSITION & ANALYSIS 188, (2017), https://doi.org/10.1016/j.jfca.2017.09.004.

[106] EFSA Panel on Additives and Products or Substances used in Animal Feed, *Scientific Opinion on the Safety and Efficacy of Iodine Compounds (E2) as Feed Additives for all Species: Calcium Iodate Anhydrous and Potassium Iodine, Based on a Dossier Submitted by HELM AG,* 11 J. EUR. FOOD SAFETY AUTH. 3101 (2013), https://doi.org/10.2903/j.efsa.2013.3101.

is important, exceeding the allowable intake can be very toxic, causing thyroid gland inflammation and thyroid cancer.

Seaweed is known to accumulate a considerable amount of iodine, though this varies among species.[107] Consumption of high amounts of seaweed can pose a potential health risk, as it is considered an iodine-rich food.[108] Iodine in seaweed is usually 100 times more than iodine levels seen in other terrestrial vegetables.[109] The level of iodine concentration depends on factors such as production and processing.[110] Also, seasonality can contribute to iodine accumulation in seaweeds. In one study, iodine concentrations in seaweed along the west coast of Italy showed a pattern with seasonality, with concentrations above average in winter and below average in summer.[111] While further studies are needed, this temperature-related flux in concentrations could be due to reactive oxygen species that form in seaweed while under heat stress levels, which cause a reaction with the antioxidant properties of iodine, resulting in release into the water column.[112]

Research shows that iodine concentrations in kelp/kombu can exceed 1,500 mg/kg, meaning an intake of just 0.5g/day of this seaweed would result in the consumption of 0.75mg of iodine. This amount exceeds the nutrient tolerable upper intake level (UL) 0.6 mg/day for adults for iodine established by the Scientific Committee on Food (SCF) and adopted by the EU. Such consumption could increase the risk of adverse effects.[113] Kelp has the highest iodine

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[107] Michael Y. Roleda et al., *Iodine Content in Bulk Biomass of Wild-Harvested and Cultivated Edible Seaweeds: Inherent Variations Determine Species-Specific Daily Allowable Consumption*, 254 FOOD CHEMISTRY 333 (2018), https://doi.org/10.1016/j.foodchem.2018.02.024.

[108] *Id.*

[109] Ana R. Circuncisão et al., *Minerals from Macroalgae Origin: Health Benefits and Risks for Consumers*, 16 MARINE DRUGS (2018), https://doi.org/10.3390/md16110400.

[110] ANSES, OPINION OF THE FRENCH AGENCY FOR FOOD, ENVIRONMENTAL AND OCCUPATIONAL HEALTH & SAFETY ON THE RISK OF EXCESS IODINE INTAKE FROM THE CONSUMPTION OF SEAWEED IN FOODSTUFFS (2018), https://www.anses.fr/en/system/files/NUT2017SA0086EN.pdf.

[111] Udo Nitschke et al., *Variability in Iodine in Temperate Seaweeds and Iodine Accumulation Kinetics of* Fucus Vesiculosus *and* Laminaria Digitata *(Phaeophyceae, Ochrophyta)*, 54 J. PHYCOLOGY 114 (2018), https://doi.org/10.1111/jpy.12606.

[112] Frithjof C. Küpper et al., *Iodine Accumulation Provides Kelp with an Inorganic Antioxidant Impacting Atmospheric Chemistry*, 105 PROC. NAT'L ACAD. OF SCI. 6954 (2008), https://doi.org/10.1073/pnas.0709959105.

[113] Banach et al., *supra* note 54.

concentration and content in food and food supplements, which have been flagged as a risk for pregnant and breastfeeding women and individuals with thyroid disorders.[114] Kelps or large brown seaweeds of the order Laminariales, such as *L. digitata*, *L. hyperborea*, *S. latissima*, and *A. esculenta*,[115] contain a higher amount of iodine, and research done in Japan reported kelp consuming populations with higher iodine-induced hypothyroidism.[116] Seaweed supplements, especially those from kelp, are not recommended for pregnant women due to amount of iodine found in them, which can cause impaired neurological development and endocrine disorders in children through placental transfer.[117] Further, mercury may interfere with iodine metabolism. It was found that prenatal mercury exposure was inversely associated with thyroid hormone levels in women who took iodine supplements during pregnancy.[118]

iii. Polycyclic Aromatic Hydrocarbons (PAHs)

Polycyclic Aromatic Hydrocarbons (PAHs) are a class of chemicals naturally found in coal, crude oil, and gasoline, and can also be produced when gas, oil, coal, forest, garbage, and other organic matter are burned, binding to form particles in the air and leading to environmental contamination.[119] The following factors contribute to PAH accumulation in seaweed: species, biology,

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[114] ANSES, *supra* note 109.

[115] Banach et al., *supra* note 54.

[116] N. Konno et al., *Association Between Dietary Iodine Intake and Prevalence of Subclinical Hypothyroidism in the Coastal Regions of Japan*, 78:2 J. CLINICAL ENDOCRINOLOGY & METABOLISM 393 (1994), https://doi.org/10.1210/jcem.78.2.8106628.

[117] M. Zimmerman & F. Delange, *Iodine Supplementation of Pregnant Women in Europe: A Review and Recommendations*, 58 EUR. J. CLINICAL NUTRITION 979 (2004), https://doi.org/10.1038/sj.ejcn.1601933; D. Caserta et al., *Heavy Metals and Placental Fetal-Maternal Barrier: A Mini-Review on the Major Concerns*, 17 EUR. REV. FOR MED. AND PHARMACOLOGICAL SCI. 2198 (2013); C.M. Taylor et al., *Lead, Cadmium and Mercury Levels in Pregnancy: The Need for International Consensus on Levels of Concern*, 5 J. DEVELOPMENTAL ORIGINS OF HEALTH AND DISEASE 16 (2014), https://doi.org/10.1017/S2040174413000500.

[118] Sabrina Llop et al., *Synergism Between Exposure to Mercury and Use of Iodine Supplements on Thyroid Hormones in Pregnant Women*, 138 ENV'T RSCH. 298 (2015), https://doi.org/10.1016/j.envres.2015.02.026.

[119] NAT'L BIOMONITORING PROGRAM, CTR. FOR DISEASE CONTROL AND PREVENTION, POLYCYCLIC AROMATIC HYDROCARBONS (PAHS) FACTSHEET (2022), https://www.cdc.gov/biomonitoring/PAHs_FactSheet.html.

concentration level around the production site, and nature of the pollutant.[120] Other accumulation factors include anthropogenic activities around the production site, oil spillage, and processing such as smoking and drying.[121] The green seaweed *Ulva compressa* accumulates more PAHs compared to red and brown species. One study found naphthalene (NAP) and benzo[a]pyrene as the major PAH pollutants across all species, with mean concentration levels of 68.57 and 56.14 parts per billion (ppb), respectively.[122] However, the accumulation rate is not considered to be a major contamination risk, as most of the studies found PAHs levels in seaweed to be below the hazard quotient (HQ) and cancer risk index (CRI) metrics established by the U.S. Environmental Protection Agency, and therefore safe for human consumption.[123]

iv. Micro- and Nanoplastics

Micro- and nanoplastics are common materials known to invade terrestrial and marine environments, due to how common they are and how quickly they can travel. They are increasing steadily in most aquatic environments and are an emerging area of study in marine ecosystems. Micro- and nanoplastics can attach to algal surfaces through electrostatic binding to cellulose in the algal tissue.[124] Seaweed can easily retain exposed microplastic on its surface.[125] In the same

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[120] Gehan M.E. Zokm et al., *Seaweed as Bioindicators of Organic Micropollutants Polycyclic Aromatic Hydrocarbons (PAHs) and Organochlorine Pesticides (OCPs)*, 29 ENV'T SCI. & POLLUTION RSCH. 34738 (2022), https://doi.org/10.1007/s11356-022-18634-z.

[121] Banach et al., *supra* note 54.

[122] Zokm et al., *supra* note 119.

[123] Fabíola H. dos Santos Fogaça et al., *Polycyclic Aromatic Hydrocarbons Bioaccessibility in Seafood: Culinary Practices Effects on Dietary Exposure*, 164 ENV'T RSCH. 165 (2018), https://doi.org/10.1016/j.envres.2018.02.013; M.A. Lage-Yusty et al., *Supercritical Fluid Extraction of Polycyclic Aromatic Hydrocarbons from Seaweed Samples Before and After the Prestige Oil Spill*, 82 BULL. ENV'T CONTAMINATION AND TOXICOLOGY 158 (2009), https://link.springer.com/article/10.1007/s00128-008-9503-9; Juan-Ying Li et al., *Safety and Quality of the Green Tide Algal Species* Ulva prolifera *for Option of Human Consumption: A Nutrition and Contamination Study*, 210 CHEMOSPHERE 1021 (2018), https://doi.org/10.1016/j.chemosphere.2018.07.076; Zokm et al., *supra* note 119.

[124] Priyanka Bhattacharya et al., *Physical Absorption of Charged Plastic Nanoparticles Affects Algal Photosynthesis*, 114 J. PHYSICAL CHEMISTRY 16556 (2010), https://doi.org/10.1021/jp1054759.

[125] Lars Gutow et al., *Experimental Evaluation of Seaweeds as a Vector for Microplastics into Marine Food Webs*, 50 ENV'T SCI. & TECHN. 915 (2016), https://doi.org/10.1021/acs.est.5b02431.

study, snails that naturally feed on this alga did not distinguish between clean algae and algae with microplastics. Plastics are often made with additives that are potentially toxic, and microplastics can accumulate toxic and carcinogenic substances, such as polychlorinated biphenyls (PCBs).[126] *Ulva* is a genus of macroalgae that commonly blooms in temperate coastal waters and is found on both the east and west coasts of the United States. *Ulva spp.* collected at locations across the New Bedford Harbor Superfund Site was found to contain PCB levels equal to or exceeding FDA tolerance levels.[127] Not only did this study find that these seaweeds could accumulate high levels of PCBs, but that the PCBs were passed through the food web to mummichogs, a keystone fish species in the area.

v. *Agrochemicals*

Agrochemicals are chemicals used in agriculture, such as herbicides, pesticides, and fertilizers. These can enter the seaweed food chain through different means, including, but not limited to, runoff from agricultural fields and treatments used to treat plants around the production sites.[128] Seaweeds may also be intentionally used as a bioremediation to remove contaminants like pesticides in water.[129] Contamination with pesticides and chemotherapeutic agents can also come directly from aquaculture activities. Benzoylphenylurea, carbamates, avermectins, and organophosphorus compounds are widely employed in aquaculture and associate to particulate matter and seaweeds owing to their hydrophobicity.[130] The reported concentrations of this hazard fall mostly below MRLs of 0.01 mg/kg as defined by the consolidated version of EU Regulation

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[126] Samaneh Karbalaei et al., *Occurrence, Sources, Human Health Impacts and Mitigation of Microplastic Pollution*, 25 ENV'T SCI. & POLLUTION RSCH. 26046 (2018), https://doi.org/10.1007/s11356-018-3508-7.

[127] Donald Cheney et al., *Bioaccumulation of PCBs by a Seaweed Bloom (*Ulva Rigida*) and Transfer to Higher Trophic Levels in an Estuarine Food Web*, 611 MARINE ECOLOGY PROGRESS SERIES 75 (2019), https://doi.org/10.3354/meps12840.

[128] Banach et al., *supra* note 54.

[129] Patrícia Anacleto et al., *Exploration of the Phycoremediation Potential of* Laminaria digitata *Towards Diflubenzuron, Lindane, Copper and Cadmium in a Multitrophic Pilot-Scale Experiment*, 104 FOOD & CHEM. TOXICOLOGY 95 (2017), https://doi.org/10.1016/j.fct.2017.01.030.

[130] R.A. Lorenzo et al., *Pesticides in Seaweed: Optimization of Pressurized Liquid Extraction and In-Cell Clean-Up and Analysis by Liquid Chromatography-Mass Spectrometry*, 404 ANALYTICAL & BIOANALYTICAL CHEMISTRY 173 (2012), https://doi.org/10.1007/s00216-012-6106-4.

(EC) No. 396/2005, although there is not enough data on the occurrences of this hazard.[131]

IMTA can add to agrochemical load depending on the species co-farmed with seaweed. Aquaculture wastewater sometimes contains remnants of chemicals from feed additives, inorganic and organic fertilizers, hormones, flocculating agents, liming agents, antibiotics, medication, pesticides, disinfectants, and therapeutants that were used during the fish farming processes.[132] Seaweed in IMTA may bioaccumulate these toxic compounds in the process of bioremediation, and the accumulation could become a potential hazard if the seaweed is consumed.

vi. Pharmaceuticals and Personal Care Products

Human and animal pharmaceuticals and personal care products (PPCPs) from sewage discharge systems have been found in seaweed farms, especially those located around residential areas and where human activities mostly occur. The presence of PPCPs was commonly attributed to sewage effluent, aquaculture, waste disposal, horticulture, or animal husbandry.[133] A study found several pharmaceuticals around seaweed producing sites, including antibiotics β-blockers and drugs for psychiatric treatments, and exposure causes accumulation of the substances.[134] However, research conducted on the occurrence of PPCPs in the seaweed cultivating environment is limited, even though they are being flagged as emerging hazards.

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[131] Banach et al., *supra* note 54.

[132] CRAIG S. TUCKER & JOHN A. HARGREAVES, ENVIRONMENTAL BEST MANAGEMENT PRACTICES FOR AQUACULTURE (2008).

[133] Banach et al., *supra* note 54.

[134] Lauren Arpin-Pont et al., *Occurrence of PPCPs in the Marine Environment: A Review*, 23 ENV'T SCI. & POLLUTION RSCH. 4978 (2016), https://doi.org/10.1007/s11356-014-3617-x; Griet Vandermeersch et al., *Environmental Contaminants of Emerging Concern in Seafood – European Database on Contaminant Levels*, 143 ENV'T RSCH. 29 (2015), https://doi.org/10.1016/j.envres.2015.06.011.

vii. Marine Biotoxins

Marine biotoxins are harmful toxins that are produced by harmful microalgae or through naturally occurring chemical reactions.[135] Dinoflagellates, which can produce toxins that can accumulate in seaweed, were found in seaweed cultivation sites.[136] Filamentous cyanobacteria, which is known to produce toxins that are poisonous to humans, were also discovered around seaweed cultivation sites.[137] Some marine biotoxin agents were found to be associated with seaweeds, including palytoxin (PTX), domoic acid (DA) and analogs, ciguatoxins, and cyclic imines (CIs).[138] However, the literature on this hazard is very limited.

viii. Persistent Organic Pollutants (POPs)

Persistent Organic Pollutants (POPs) are pollutants that accumulate in the environment over a period of time. If seaweed is being cultivated in a contaminated site, it tends to suck up the accumulated hazard. The influencing factors are the cultivating environment and the seaweed species itself.[139] Reports have noted *Ulva rigida* (a green seaweed species) to increasingly take up POPs from cultivation areas.[140] However, there is a limited amount of research on this pollutant in macroalgae.

B. Microbial Hazards

Microbial hazards are hazards from microorganisms present in air, food, water, soil, animals, and the human body, and can occur during cultivation,

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[135] Banach et al., *supra* note 54; FOOD & AGRIC. ORG., *supra* note 83.
[136] FOOD & AGRIC. ORG., *supra* note 83.
[137] ANA AFONSO ET AL., EUR. FOOD SAFETY AUTH., TECHNICAL REPORT ON ESFA'S ACTIVITIES ON EMERGING RISKS IN 2016 (2017), https://doi.org/10.2903/sp.efsa.2017.EN-1336.
[138] Banach et al., *supra* note 54.
[139] *Id.*
[140] Donald Cheney, *Toxic and Harmful Seaweeds*, *in* SEAWEED IN HEALTH AND DISEASE PREVENTION 407-421 (Ira A. Levine & Joël Fleurence, eds., 2016), https://doi.org/10.1016/B978-0-12-802772-1.00013-0; Donald Cheney et al., *Uptake of PCBs Contained in Marine Sediments by the Green Macralga* Ulva rigida, 88 MARINE POLLUTION BULL. 207 (2014), https://doi.org/10.1016/j.marpolbul.2014.09.004.

growth, harvest, transportation, processing, handling, and storage of seaweed.[141] Exposure to these hazards causes foodborne illnesses and can be toxic.
The list of microbial hazards is not as lengthy as chemical hazards. Possible microbial hazards in seaweed include pathogenic bacteria, norovirus, prions, and parasites such as trematodes. Microbial hazards can occur through the various supply chains, including harvest, production, processing, transportation, and packaging.[142]

i. Pathogenic Bacteria

Major factors influencing pathogens in seaweed include the cultivation site, handling, storage, heat treatment, poor hygiene, and sanitation around the cultivation site and processing facilities, as well as the people handling the seaweed, and proximity to wildlife populations such as in a refuge.[143]

The risk of human exposure to pathogenic bacteria is higher when contaminated seaweed is consumed raw.[144] However, drying was found to reduce bacterial load to some extent.[145] Studies show that major foodborne disease pathogens, such as those from *Vibrio parahaemolyticus* and *Vibrio vulnificus*, are easily accumulated around coastlines, where seaweeds are usually farmed or harvested.[146] While studies on these are limited, *Escherichia coli*, *Vibrio spp.*, and *Salmonella enterica* were found in several seaweed species.[147] In the U.S., an assessment was performed on sugar kelp in Maine bays, which found low levels of *E. coli*, *V. parahaemolyticus*, and *V. alginolyticus* in samples at all study sites. The study also found *S. enterica* on sugar kelp from 83% of sampling events

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[141] FOOD & AGRIC. ORG., *supra* note 81.
[142] Banach et al., *supra* note 54; Banach et al., *supra* note 57.
[143] Banach et al., *supra* note 54; Banach et al., *supra* note 57; FOOD & AGRIC. ORG., *supra* note 83.
[144] FAO, *supra* note 83.
[145] Shin Y. Park et al., *Synergistic Effects of NaOCl and Ultrasound Combination on the Reduction of* Escherichia coli *and* Bacillus cereus *in Raw Laver*, 11:5 FOODBORNE PATHOGENS & DISEASE 373 (2014), https://doi.org/10.1089/fpd.2013.1665.
[146] Zahid H. Mahmud et al., *Seaweeds as a Reservoir for Diverse* Vibrio parahaemolyticus *Populations in Japan*, 118:1 INT'L J. FOOD MICROBIOLOGY 92 (2007), https://doi.org/10.1016/j.ijfoodmicro.2007.05.009.
[147] Banach et al., *supra* note 54.

during the study.[148] *V. vulnificus*, which poses a significant threat to human health along the U.S. Gulf coast, was found in seaweed samples along the coast of Japan.[149]

Processing contaminated seaweed through heating does not always eliminate the risk exposure and can even add more hazardous bacteria to already existing ones.[150] *Bacillus licheniformis* and *Bacillus pumilus,* two toxin producing, spore-forming bacteria, were detected following a heat-treatment of seaweed.[151] While bacterial levels reported in the above studies were relatively low, the presence alone indicates that care should be taken when developing management, processing, and storage practices for the harvest of seaweed along coastlines.

ii. Viruses

Viruses, such as norovirus and hepatitis E virus, have been found in edible seaweed species, and exposure can occur during cultivation, harvest, or processing.[152] Norovirus is among a gastroenteritis group of viruses that spread quickly, commonly known to inflame the stomach and intestine lining and cause severe diarrhea and vomiting in infected patients. Hepatitis E virus is commonly found in the stool of an infected person and can spread even in microscopic quantities. The main route of these viruses in seaweed is foodborne, mostly from pig and wild boar.[153] The first recorded norovirus outbreak in South Korea was in two different schools where seasoned green seaweeds were eaten. Although multiple norovirus genotypes were detected in the students' food samples, a

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[148] Olivia N. Barberi et al., *Assessment of Bacterial Pathogens on Edible Macroalgae in Coastal Waters*, 32 J. APPLIED PHYCOLOGY 683 (2019), https://doi.org/10.1007/s10811-019-01993-5.

[149] Zahid H. Mahmud et al., *Occurrence, Seasonality and Genetic Diversity of* Vibrio vulnificus *in Coastal Seaweeds and Water Along the Kii Channel, Japan*, 64:2 FEMS MICROBIOLOGY ECOLOGY 209 (2008), https://doi.org/10.1111/j.1574-6941.2008.00460.x.

[150] Banach et al., *supra* note 54; Banach et al., *supra* note 57.

[151] Banach et al., *supra* note 54.

[152] Banach et al., *supra* note 54; Banach et al., *supra* note 57.

[153] Banach et al., *supra* note 54.

significant amount of this virus was linked to the seaweed.[154] However, very few reports have noted viruses, and therefore limited information is available about them in edible seaweeds.

C. Physical Hazards

Physical hazards are objects or materials that are introduced to seaweed unintentionally and when consumed, can pose considerable risk to human health. Physical hazards include small pebbles and pieces of shells, metal, plastic, and glass that are generally greater than 0.3 inches in size, although foreign objects smaller than this may cause trauma and injury in special risk groups like infants or the elderly. These material fragments can easily be found in harvested seaweeds[155] They can also be introduced during production, transportation, processing, storage, or packaging.

D. Allergenic Hazards

Allergenic hazards are a type of hazard found in foods, where some people have an allergic reaction to specific proteins which may be present in the food. An allergic reaction can cause mild symptoms or a major reaction. Major allergenicity influencing factors for edible seaweed include seaweed type and cultivation site.[156] Although there is currently limited information about the allergenicity of proteins present in seaweed, at least one study has identified food allergens in green seaweed *Ulva*.[157] Other studies have found that there are protein structures in dried nori similar or identical to immunoreactive components related to immunoglobulin E-mediated allergies, which are also found in crustaceans. Therefore, people who react to crustacean species are likely to also be allergic to nori seaweed (*Porphyra* spp).[158] A study of seaweeds cultivated in

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[154] J.H. Park et al., *First Norovirus Outbreaks Associated with Consumption of Green Seaweed (*Entermorpha spp.*) in South Korea*, 143 EPIDEMIOLOGY & INFECTION 515 (2015), https://doi.org/10.1017/S0950268814001332.

[155] FOOD & AGRIC. ORG., *supra* note 83.

[156] *Id.*

[157] Banach et al., *supra* note 54.

[158] Tomohiro Bito et al., *Bioactive Compounds of Edible Purpler Laver Porphyra sp. (Nori)*, 65 J. AGRIC. & FOOD CHEMISTRY 10685 (2017), https://doi.org/10.1021/acs.jafc.7b04688.

Long Island Sound, as well as other areas with the presence of fouling organisms including crustacean shellfish known to contain the protein tropomyosin, suggested the potential for ingestion-related allergic reactions.[159] Immunoglobulin E-mediated patients were also found to react to some red seaweeds species, such as *Porphyra*, *C. crispus*, and *P. palmate.*[160]

VI. CLIMATIC INFLUENCE ON FOOD SAFETY HAZARDS OF EDIBLE SEAWEED

Climatic changes that occur because of shifting temperatures and weather patterns, and changes in seawater chemistry, can significantly complicate and/or amplify already present hazards. Anthropogenic climate change, being the major driving force due to burning of fossil fuels, deforestation, landfills, the effects of overpopulation, and other human related activities, can lead to dramatic changes in localized, nearshore areas where the vast majority of seaweed aquaculture takes place. Seaweeds play an important ecological role in coastal habitats, yet they can still become vulnerable to both physical and chemical changes in the marine environment.[161] Major threats from climatic changes include, but are not limited to, the development and escalation of harmful algal blooms (HABs) and marine heat waves, both strongly influenced by rising temperatures in production waters. HABs are colonies of toxic algae that grow quickly, resulting from warmer water temperatures, excess nutrients, and sunlight. HABs act as a water contaminant and can cause human health hazards. Such blooms can lead to shifts in the typical species composition of coastal ecosystems.[162] Literature supports the idea that extreme weather events and warming due to climate change could be increasing

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[159] ANOUSHKA CONCEPCION ET AL., SEAWEED PRODUCTION AND PROCESSING IN CONNECTICUT: A GUIDE TO UNDERSTANDING AND CONTROLLING POTENTIAL FOOD SAFETY HAZARDS (2020), https://seagrant.uconn.edu/wp-content/uploads/sites/1985/2020/01/Seaweed-Hazards-Guide_Jan2020_accessible.pdf.

[160] Iason Thomas et al., *Seaweed Allergy*, 7 J. ALLERGY & CLINICAL IMMUNOLOGY 714 (2019), https://doi.org/10.1016/j.jaip.2018.11.009.

[161] Christopher D. G. Harley et al., *Effects of Climate Change on Global Seaweed Communities*, 48 J. PHYCOLOGY 1064 (2012), https://doi.org/10.1111/j.1529-8817.2012.01224.x.

[162] Kristen L. Wilson et al., *Effects of Increasing Water Temperatures on Survival and Growth of Ecologically and Economically Important Seaweeds in Atlantic Canada: Implications for Climate Change*, 162 MARINE BIOLOGY 2431 (2015), https://doi.org/10.1007/s00227-015-2769-7.

blooms of *Sargassum sp.* in the Caribbean.[163] A rise in temperature was also noted to aggravate the escalation of a HAB called red tide in Florida's southwest coast.[164]

In another study, a marine heatwave was found to impact resistance, bleaching, changes in abundance, species invasions, and local to regional extinctions.[165] A rise in arsenic accumulation was higher in *Fucus spiralis* and *Ascophyllum nodosum* seaweed species in elevated sea surface temperatures.[166] A preliminary report discovered an increase in water temperature can make fish and seaweed absorb more mercury.[167] Another report found increased iodine accumulation in seaweed used for carbon sequestration, thereby increasing the hazard level.[168]

VII. CONCLUSIONS

While seaweed is an important part of the global food system and can provide nutritional benefits, there are a number of food safety concerns. From a science and sampling perspective, information exists only for those contaminants that researchers actively test for. There are significant deficiencies in monitoring seaweed for potential food safety risks, and it would benefit governments to create a standardized sampling program, as well as to share data regarding food safety testing.

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[163] Candace A. Oviatt et al., *What Nutrient Sources Support Anomalous Growth and the Recent Sargassum Mass Stranding on Caribbean Beaches? A Review*, 145 MARINE POLLUTION BULL. 517 (2019), https://doi.org/10.1016/j.marpolbul.2019.06.049.

[164] Angela Fritz, *How Climate Change is Making 'Red Tide' Algal Blooms Even Worse*, THE WASH. POST (Aug. 15, 2018), https://www.washingtonpost.com/news/capital-weather-gang/wp/2018/08/14/how-climate-change-is-making-red-tide-algal-blooms-even-worse/ .

[165] Sandra C. Straub et al., *Resistance, Extinction, and Everything in Between – The Diverse Responses of Seaweeds to Marine Heatwaves*, 6 FRONTIERS MARINE SCI. (2019), https://doi.org/10.3389/fmars.2019.00763.

[166] FOOD & AGRIC. ORG., *supra* note 83.

[167] Park et al., *supra* note 144.

[168] Dong Xu et al., *Ocean Acidification Increases Iodine Accumulation in Kelp-Based Coastal Food Webs*, 25 GLOB. CHANGE BIOLOGY 629 (2019), https://doi.org/10.1111/gcb.14467.

Furthermore, in the United States, federal guidance is required to set limits for the food safety risks discussed within this paper. Given the large number of contaminants that exceed regulated safety limits in other countries, the U.S. should likewise set safety limits. Existing regulations vary substantially by country within Europe, with some MRLs codified by the EU. However, countries like France have also set their own recommended or legal maximums which may or may not be as stringent. China also has a number of guidelines in place for food safety considerations for seaweed consumption. It is important for the U.S. to follow suit and create safety limits for seaweed consumption given the emphasis on increasing seaweed cultivation during Blue Economy discussions,[169] as well as through U.S. federal grants programs such as those run by the Department of Energy's Advanced Research Projects Agency-Energy.

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[169] Beatrice Crona et al., *Four ways blue foods can help achieve food system ambitions across nations*, 616 NATURE 104 (2023), https://www.nature.com/articles/s41586-023-05737-x.