Food safety during seaweed cultivation at offshore wind farms: An exploratory study in the North Sea

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ABSTRACT

Multi-use in ocean space, and seas, entails the co-location of different industries or technologies and their corresponding activities that take place at the same time in a specific location. This concept focuses on finding solutions to tackle global challenges in food security. However, the effects that seaweed cultivation at offshore wind farms may have on food and feed safety are less readily addressed. This study examined whether currently available food and feed safety standards for seaweed can be applied to multi-use activities at sea. The focus was on the combined use of seaweed cultivation at an offshore wind farm in the North Sea. Literature regarding food safety hazards in seaweed was screened, and standards were evaluated. Expert elicitation on seaweed cultivation was retrieved via in-depth interviews and a workshop. Results showed that although some food safety hazards may be more apparent for seaweed cultivation such as toxic metals (e.g., arsenic, cadmium) and iodine, others may become relevant when considering multi-use (e.g., allergens, polycyclic aromatic hydrocarbons, toxic metabolites). Key factors for food safety include the location of seaweed cultivation, handling and processing of seaweed, and seaweed testing. Public standards, the Food Safety System Certification 22000 standard, and the Marine Stewardship Council/Aquaculture Stewardship Council standard are recommended for the food and marine sectors to consider when determining standards to implement. This case study provides an example of how to address seaweed food and feed safety in a multi-use scenario in the North Sea. We recommend additional case studies for other multi-use at sea scenarios.

1. Introduction

Globally, the need to feed a growing population and to combat the negative influence of climate change on food production means alternative strategies for food cultivation and production are required. Large-scale seaweed farming can be a solution to help tackle the global challenge of food security while providing a potentially positive impact on the environment. Seaweed production is increasing, and with it, the idea that seaweed production could operate during multi-use activities at sea. Multi-use activities at sea have been described for discipline-specific governance and planning purposes (e.g., for marine spatial planning), socio-economic aspects [2, 3], environmental aspects [4], and engineering aspects [5]. However, the exploration of the effects that seaweed cultivation at offshore wind farms may have for food and feed safety purposes are less readily addressed in the scientific literature. Therefore, it is important to evaluate how food safety governance and marine food production and policy for seaweed production could operate during multi-use activities at sea.

Previous food safety concerns have given rise to the development of food safety governance, consisting of both regulatory legislation, including public standards, and business-initiated voluntary measures, including private standards. Food and feed business operators in the European Union (EU) are legally responsible for meeting the requirements set out to satisfy food law, including verification thereof, at all stages of production, processing, and distribution [6]. This study aims to examine currently available food and feed safety standards for seaweed production and to determine whether these can be applied to multi-use activities at sea that aim to make use of seaweed for food and
feed purposes. The focus of this study was the combined use of seaweed cultivation at offshore wind farms in the EU, with an exploration in the North Sea. Questions regarding (i) which food and feed hazards arise and (ii) which standards are relevant to manage food and feed safety concerns were addressed.

2. Materials and methods

2.1. Literature

To better identify key standards to ensure safe food and feed coming from seaweed, the literature on potential hazards in seaweed was scanned. The work of van der Spiegel, Noordam and van der Fels-Klerx [7] and van den Burg, Stuiver, Veenstra, Bikker, Contreras, Palstra, Broeze, Jansen, Jak and Gerritsen [8] were mainly consulted to identify relevant food and feed safety hazards that may be of public health concern in the EU. The seaweeds mentioned by van der Spiegel, Noordam and van der Fels-Klerx [7] were those meant for direct consumption; these were indicated as Ascophyllum nodosum, Cladophora glomerata, Eisenia bicyclis (currently accepted taxonomically as Ecklonia bicyclis), Enteromorpha spp. (currently accepted taxonomically as Ulva spp.), Fucus vesiculosus, Hizikia fusiforme (currently accepted taxonomically as Sargassum fusiforme), Laminaria spp., Micrasterias floscosa, Monostroma spp., Palmaria palmata, Porphyra spp., Ulva rigida, and Undaria pinnatifida. Additionally, the work of van den Burg, Stuiver, Veenstra, Bikker, Contreras, Palstra, Broeze, Jansen, Jak and Gerritsen [8] included information on the following seaweeds, which are endemic to the North Sea area: Laminaria digitata, P. palmata, Saccharina latissima, and Ulva lactuca. Moreover, information from the European Food Safety Authority (EFSA) on emerging risks from microbiological hazards like Norovirus and marine biotoxins, among others, were considered [9].

Literature to identify public and private standards related to food and feed safety were searched via the Scopus database and Google Scholar. Moreover, standards were collected from the Codex Alimentarius website (http://www.fao.org/fao-who-codexalimentarius/en/), EU legislation from the EUR-Lex website (https://eur-lex.europa.eu/homepage.html), and scientific reports from governmental organizations such as the EFSA.

2.2. Expert elicitation

Expert elicitation was used to evaluate food and feed safety concerns and related standards of seaweed production in a multi-use setting. It was elicited in two ways: (i) with in-depth interviews and (ii) during a stakeholder workshop. Terminology regarding food safety concepts like risk analysis as well as public and private standards were used as input for the interviews and workshop (Supplementary data A).

2.2.1. Interviews

The interviews addressed public and private standards for food and feed production. The interviews identified: (i) current or potential food or feed safety concerns relevant to seaweed and seaweed aquaculture, (ii) standards and regulations currently used to deal with these concerns, (iii) concerns which are not yet covered in these standards and regulations, and (iv) the potential role of a new (private) standard for cultivated seaweed. Eleven experts were approached to participate in these qualitative interviews, of which nine agreed to partake. In-depth interviews were conducted with these nine stakeholders involved with different aspects of seaweed. The interviewees included a seaweed producer (1), producer and processor (1), trader (1), business innovator (1), a retailer (1), a certification body (1), and national governmental authorities (3). Interviews were conducted using a semi-structured approach using a pre-defined questionnaire. The interview guide is shown in Supplementary data B.

2.2.2. Workshop

During a two-day stakeholder workshop, 32 experts involved in safety aspects of offshore multi-use activities gathered and discussed potential food and feed safety hazards given the combined use of seaweed cultivation at offshore wind farms in the North Sea. Experts attended from organizations such as the Alfred Wegener Institute (Bremerhaven), Shell/NoordzeeWind, NoordzeeBoerderij, Rijkswaterstaat, Control Union Certifications (a certifying body), the Netherlands Food and Consumer Product Safety Authority, and Wageningen University & Research. Experts were first presented with the concept of food safety risk analysis, including the distinctions between hazards and risks (Supplementary data A). Also, the potential food and feed hazards related to seaweed were outlined (Table A1).

Afterward, three group sessions were held in which scenarios were presented and discussed. The waters of the North Sea are one of the busiest areas in the world. As an extensively used sea that is searching for opportunities for combined use, the effects of shipping traffic illustrate a situation where these scenarios may be greatly challenged. Experts were provided with the following five scenarios that may occur at a seaweed farm located between the wind turbines of an offshore wind farm in the North Sea: (i) a collision or a sinking vessel, (ii) the release of materials from substrates and equipment, (iii) the effect of climate change, (iv) the influence of increased sea life/competition, and (v) specific effects that can occur due to the combined effects that occur during integrated aquaculture. Other scenarios and topics were welcomed during each of the three group sessions, of which there were at least seven unique attendees per session. During these sessions, the input from the experts was written down. The results were compiled into a concluding workshop presentation, where attendees had the opportunity to provide final remarks.

3. Results and discussion

3.1. Seaweed hazards

Several chemical hazards were identified as potential hazards. Table A1 describes the most relevant hazards in seaweed, based on screening the literature and expert elicitation. Other relevant hazards were microbiological hazards such as Salmonella spp., Bacillus cereus, or Norovirus as well as physical hazards such as micro- or nanoparticles from plastics. For some contaminants, including toxic metals and iodine, sufficient knowledge is available to conclude on their effect. For most contaminant, however, the currently available knowledge is too limited to conclude about their possible occurrence in seaweed, let alone the impact when considering multi-use activities at sea. Other hazards were proposed that may be relevant for multi-use at sea of seaweed for food and feed purposes such as allergens, polycyclic aromatic hydrocarbons (PAHs), and toxic metabolites. Knowing which hazards could potentially be of concern can help to shape current standards and to avoid that hazards become risks.

3.2. Public and private standards

Standards can fall into a spectrum of public-mandatory, public-voluntary, private-mandatory, or private-voluntary. Often public standards can be categorized as mandatory, as in the case for Codex Alimentarius or EU legislation. However, public standards can also be voluntary; an example is the ‘Label Rouge’ developed by the French government [10]. Several private voluntary food safety standards are global (Good Agricultural Practice (GAP), Good Manufacturing Practice (GMP), etc.) or international (e.g., the International Organization for Standardization (ISO)). Although private standards are typically voluntary, they can also range from voluntary to mandatory. For example, private standards often make use of principles laid out in public standards, e.g., the British Retail Consortium (BRC), and the Global Standard for Food Safety adheres to the Hazard Analysis and
Critical Control Point (HACCP) principles; thus, some principles are mandatory for private standards.

3.2.1. Public standards

Food and feed safety is reflected in international standards for trade (Codex Alimentarius, General Agreement on Tariffs and Trade (GATT), Agreement on Sanitary and Phytosanitary Measures (SPS Agreement), Agreement on Technical Barriers to Trade (TBT Agreement), etc.) as well as EU legislation like the General Food Law (GFL). Also, the Food and Agriculture Organization of the United Nations (FAO) has a Code of Conduct for Responsible Fisheries, which also applies to seaweed aquaculture, and outlines the importance of food safety in aquaculture. More specific standards for food safety exist which specify maximum allowable concentrations of contaminants that could be present in food or feed ingredients. The public standards described in the following sub-sections are identified as being relevant for seaweed that we are to used for food.

3.2.1.1. Codex Alimentarius. The Codex Alimentarius (Food Code) is a collection of internationally recognized standards, codes of practice, guidelines, and other recommendations related to food, food production, food safety, and food hygiene, e.g., with the latter in the form of HACCP systems. These are adopted by the Codex Alimentarius Commission (CAC), which is a central part of the Joint Food and Agriculture Organization of the United Nations (FAO)/World Health Organization (WHO) Food Standards Programme. Processed, semi-processed, or raw foods, as well as topics like food labeling, additives, contaminants, etc., are included [11].

Codex Members are coming from 188 Member Countries and one Member Organization (EU). Of these Codex Members, Marinalg International (World Association of Seaweed Processors) is a non-governmental organization (NGO) that supports the interests of seaweed farmers, consumers, and the hydrocolloids industry. They represent the regulatory interest of the seaweed processing industry to international bodies like the Codex Alimentarius, EU, and national regulatory authorities [12].

3.2.1.2. Codex standards, codes of practice and guidelines. Codex standards can be vertically based, meaning they address principal foods or commodities, or horizontally based standards, which are often termed “general.” Codex standards specific to seaweed or algae are limited. However, the “Regional standard for laver products” (CXS 323R-2017) is available. It concerns laver products, being dried, roasted, or seasoned thereof and which belong to the genus Pyropia [13]. Although not directly related to seaweed, the “Standard for live and raw bivalve molluscs” (CODEX STAN 292–2008) may be of use when considering possible hazards for multi-use scenarios (e.g., concerning marine biotoxins as a hazard) [14]. Also, other codes of practice and guidelines can be consulted such as the “Code of practice for fish and fishery products” (CAC/RCP 52–2003) [15], “Guidelines on the application of general principles of food hygiene to the control of pathogenic Vibrio species in seafood” (CAC/GL 73–2010) [16], and “Principles and guidelines for the establishment and application of microbiological criteria related to foods” (CAC/GL 21–1997) [17], and “The code of hygienic practice for low-moisture foods” (CAC/RCP 75–2015) [18].

Despite the unspecific reference to seaweed, several general Codex standards can be considered, including the use of seaweed as a food additive in other foodstuffs such as dairy products, as an additional ingredient, or as packaging in drinks (Supplementary Data C, Table C1). Given developments in seaweed cultivation, production, extraction, and use, Codex standards are important to realize for food and feed applications, and should also be considered given multi-use activities at sea.

Besides Codex standards, several codes of practice and guidelines exist. For example, the CAC outlines the principles of HACCP and guides the application thereof in CAC/RCP 1–1969 “General principles of food hygiene” (last revised in 2003). Also, guidelines like CXG 92–2019 “Guidelines for rapid risk analysis following instances of detection of contaminants in food where there is no regulatory level,” among others, outline principles on topics such as monitoring, methods for analyses, and further control of hazards.

3.2.1.3. Hazard Analysis and Critical Control Points (HACCP). Since its publication, HACCP has gained international acceptance as a key tool for food safety management. A HACCP system allows businesses to focus on control at critical points. There are several preliminary steps before the seven HACC principles can be applied (Supplementary Data C, Fig. C1). Although HACC is also described in Regulation (EC) 178/2002 and Regulation (EC) 852/2004, private standards often refer to the one established in the Codex Alimentarius. Nonetheless, for businesses to be able to apply HACC, they must be consistent with the “Codex general principles of food hygiene,” which includes prerequisite programs that consist of, among others, training and verification.

3.2.1.4. EU legislation. The European Parliament and the Council adopted Regulation (EC) 178/2002 (the GFL), which establishes general principles, requirements, and procedures for food and feed at the EU and national levels. It provides a framework for food and feed safety covering, among others, responsibilities for food and feed business operators at all stages of production, processing, and distribution, the role of the EFSA, the rapid alert system, and crisis management [6]. The objective of the regulation is to ensure a high level of consumer protection, while also considering animal health and welfare, plant health, and the environment.

Other legislation relevant to food and feed safety of seaweed is provided (Table 1). Aspects such as hygiene, novelty, hazardous substances,
labeling, additives, production, and control are described. For example, legislation on organic seaweed production, including the collection and farming thereof, can be found in Commission Regulation No (EC) 710/2009. Moreover, the previously known Novel Foods Regulation (EC) 258/97 evaluated novel food and food ingredients in the EU. Notably, novel food has been considered as food not consumed to a significant degree by humans in the EU before May 15, 1997. From January 1, 2018, Regulation (EU) 2015/2283, which repeals Regulation (EC) 258/97, was applied; some exceptions are stated in Article 36 of said regulation.

Moreover, the European Parliament and the Council adopted Regulation (EC) 882/2004, which relates to the official controls and verification of compliance with food and feed law, animal health, and welfare. The regulation aims to create an integrated and uniform approach to official controls along the agri-food chain by allowing competent authorities in the member states to verify compliance. The regulation was reviewed and, given a transition period, will be replaced by the Official Controls Regulation (EU) 2017/625. In addition to repealing Regulation (EC) 882/2004, several additional pieces of legislation will be repealed or amended. Regulation (EU) 2017/625 was officially adopted on March 15, 2017, and has a main application date of December 14, 2019. Given the novel nature of multi-use production of seaweed at sea for food and feed purposes, the requirements laid down in EU legislation should be carefully considered for multi-use in the EU.

3.2.2. Private standards

Several private standards are developed and used in food and feed chains. Private standards ensure producers and users along the supply chain have a shared understanding of food or feed safety issues and communicate on identified hazards and mitigation measures. Private standards can reduce consumers’ uncertainty and information asymmetry about product characteristics such as safety, quality, and social and environmental aspects. They can be used as strategic tools to differentiate a firm’s products, to improve bargaining power over their suppliers, or to pre-empt government regulations [19]. Food and feed safety is an area where retailers maintain food safety and quality standards that are often more stringent than public standards; 70%–80% of retailers assess their private standards slightly or significantly higher than public standards [20]. The private standards described in the following sub-sections are identified as being relevant for seaweed.

3.2.2.1. International Organisation for Standardisation (ISO). ISO 22000-2018 (EN) is a standard that specifies requirements for a food safety management system (FSMS). To obtain certifications, organizations need to demonstrate the ability to control food safety [21]. ISO 22000-2018 (EN) applies to all organizations, regardless of the size and activity in the food chain. The standard specifies requirements to enable an organization to plan, implement, operate, maintain, and update an FSMS aimed at providing products that, according to their intended use, are safe for the consumer. This results in an FSMS that can comply with applicable statutory and regulatory food safety requirements; can evaluate and assess customer requirements; and effectively communicate food safety issues to suppliers, customers and relevant interested parties in the food chain. ISO 22000-2018 (EN) is certified by an external organization, although companies can do a self-assessment and self-declare conformity to the standard.

Traceability is further tackled in ISO 22005-2007 (EN). Traceability is defined as the ability to trace and follow a food, feed, food-producing animal, or substance intended to be, or expected to be incorporated into food or feed, through all stages of production, processing, and distribution. ISO 22005-2007 gives the principles and specifies the basic requirements for the design and implementation of a feed and food traceability system. Like ISO 22000-2005, it can be applied by an organization operating at any step in the feed or food chain and is intended to be flexible enough to cover different food products and companies working at different steps in the chain.

3.2.2.2. GMP + Feed Safety Assurance (FSA). GMP + Feed Safety Assurance (FSA) is a module for the assurance of feed safety in all the stages and for all actors of the feed supply chain. Demonstrable assurance of feed safety is a “license to sell” in many countries and markets; participation in the GMP + FSA module can facilitate this. Based on practical needs, multiple components have been integrated into this module, such as requirements for the quality management system (ISO 9001), HACCP, product standards, traceability, monitoring, pre-requisites programs, chain approach, and early warning systems. GMP + FSA can be audited and certified by a third-party.

3.2.2.3. Global Food Safety Initiative (GFSI). The Global Food Safety Initiative (GFSI) is an industry-driven initiative to guide FSMSs necessary for safety along the supply chain, tackling the proliferation of private standards. The GFSI is a shared effort to harmonize the dissonance among these competing standards [22]. GFSI is not a scheme in itself, and neither does it carry out any accreditation or certification activities. A food safety management program is “recognized” by GFSI when it meets internationally recognized minimum food safety requirements. An analysis of the applicability of recognized certification programs for seaweeds, acknowledged under GFSI, illustrates that there is not one fully applicable standard, but various could be relevant, depending on the categorization of seaweed. If it fits the category “food or feed,” certified standards would include Safety Quality Food (SQF) Code 7th edition, level 2. For the category “BI – Farming of Plants,” the following certification programs are recognized: PRIMUS GFS Standard (v2.1 – December 2011); GLOBALG.A.P. integrated farm assurance scheme version 5, produce safety standard version 4, and harmonized produce safety standard; CanadaGAP scheme version 6, options B, C, and D and program management manual version 6; and SQF Code 7th edition, level 2 and Japan GAP Foundation. If seaweed farming is considered a form of fish farming, there is one recognized certification program: GLOBALG.A.P.

3.2.2.4. Good Agricultural Practice (GAP). GAP standards have been developed by the food industry and producer organizations to formulate standards for agricultural practices at the farm level [23]. Under GAP, the GLOBALG.A.P. Aquaculture Standard applies to a diversity of fish, crustaceans, and mollusks and extends to hatchery-based farmed species as well as the passive collection of seedlings in the planktonic phase. It covers the production chain, from broodstock, seedlings and feed suppliers, to farming, harvesting, and processing. Aquaculture producers are required to source the compound feed used at the aquatic farming and hatchery levels from reliable suppliers. The GLOBALG.A.P. Chain of Custody Standard seeks to secure a high level of transparency and integrity by identifying the status of products throughout the entire production and supply chain, from farm to retailer.

3.2.2.5. British Retail Consortium (BRC) Global Standard for Food Safety. The BRC standard emerged as a voluntary consensus standard. It is a joint action of retailers and their interest groups [24]. They are often a fundamental requirement of leading retailers, manufacturers, and foodservice organizations. Companies need to fulfill several criteria to be able to comply. They need to show acknowledgment of the importance of management commitment, through the implementation of a quality management system and comply with HACCP regulations. Consistent auditing must be in place, e.g., by identifying areas that often have the highest rate of product recalls and withdrawals, such as labeling and packing. Systems to reduce exposure to food fraud need to be developed, and companies need to promote greater resilience.

1. The list was prepared on 2018-12-17 and might change over time. For more information, see https://www.mygfsi.com/certification/recognised-certification-programmes.html.
transparency, and traceability in the supply chain.

3.2.2.6. Food Safety System Certification (FSSC) 22000. The Food Safety System Certification (FSSC) 22000 aims to demonstrate that a company has a robust FSMS in place that meets the requirements of its customers and consumers. FSSC 22000 is a full certification scheme for FSMSs based on ISO 22000:2005 and ISO/TS 22002-1:2009. FSSC 22000 includes transport and storage activities performed by the companies producing/processing in the food industry [25].

3.2.2.7. Marine Stewardship Council (MSC)/Aquaculture Stewardship Council (ASC). The Marine Stewardship Council (MSC) and Aquaculture Stewardship Council (ASC) have developed as international partnerships between lead firms and NGOs setting their own sustainability standards for seafood [26]. Recently MSC and ASC released a joint standard for sustainable seaweed production, setting several requirements for seaweed harvesting and farming practices. In this standard, performance indicators are formulated to assess the impacts on wild seaweed populations, environmental impacts, effective management, social responsibility, and community relations and interactions. For the North Sea, the MSC/ASC standard is the only known private certification focused on seaweed.

3.2.2.8. Organic certification. Organic certification of seaweeds is already regulated through Regulation (EC) 710/2009 (Table 1). Although this regulation has been the basis for labeling seaweeds in some European countries like France, other countries do not have certified seaweed producers. The Dutch control organization SKAL Biocontrole started the organic certification of seaweed producers and processors in 2017.

3.3. Expert elicitation

Since this is an exploratory study, expert elicitation can provide additional insight into the current state of seaweed production, including the potential opportunities for multi-use at an offshore wind farm in the North Sea.

3.3.1. Interviews

Table 2 summarizes the findings per interviewed stakeholder based on the four pre-identified objectives of the interviews. Identified concerns related to food and feed safety that were relevant for seaweed mostly focused on single-use activities, except for the increased risk of oil spills as noted by governmental authorities. From the stakeholder interviews, three food safety issues relevant to seaweed production were identified: the cultivation location, seaweed handling and processing, and seaweed testing.

First, the location of seaweed cultivation is essential to avoid contamination. Cultivation should be in an area where contamination of land or human-based activities is not expected. This concurs with current research, which notes the potential contamination of seaweed due to anthropogenic activities [27]. For example, sewage and waste emissions from activities need to be avoided so that seaweed does not become contaminated. Besides contamination of the seaweed product, the retailer expressed concerns with potential contamination in the water or the surrounding environment where the seaweed is cultivated. Location is a fundamental condition that can be problematic to fulfill, especially considering multi-use needs for shared space. There is a tradeoff with optimal growth conditions (e.g., the nitrogen availability) and product quality.

Next, seaweed handling, including further processing thereof, is another relevant issue described. Seaweed storage after harvest is critical to avoid decay. For instance, the way of harvesting seaweed (when cutting off the line) and means of storage in holds or tubes of seawater are other practices that may help to keep the freshness of seaweed before processing. HACCP can help guide how to adhere to food hygiene, although some stakeholders seek specific templates or tools to apply such standards. On the other hand, the lack of urgency for (private) standards for seaweed, ambiguity on a common method for seaweed cultivation, and the costs for certification (especially costs incurred by those who first initiate the standard) were described by stakeholders when asked about the possibility for new standards concerning seaweed.

Finally, a third issue described by stakeholders concerned with seaweed testing for contaminants, including heavy metals (cadium, mercury), arsenic, and iodine were often noted. Concerns about the limited differentiation between organic and inorganic arsenic have become problematic for governmental authorities, among other stakeholders. The need to differentiate arsenic in seafood has been expressed by the EFSA, as exposure to inorganic arsenic, the more toxic form, should be reduced [28]. As for iodine, the content changes between seasons was noted as a factor that could affect iodine content. However, studies on the iodine content of seaweeds have shown that other factors, like sampling location, may significantly influence iodine content [29].

For some European countries, seaweed access to the market has been a question given iodine levels, yet this does depend on the product in question and purpose thereof. Also, the interviewed seaweed trader identified a concern with the traceability of products, which is also a relevant issue given a multi-use setting. Additional concerns noted by governmental authorities included microorganisms on seaweed or from storage thereof (e.g., Salmonella spp.), toxic metabolites (e.g., marine biotoxins), as well as phytotoxins. Besides these, other unknown or emerging hazards not yet investigated may be of concern. For example, allergens from other marine-based products grown near seaweed (e.g., during integrated multi-trophic aquaculture (IMTA) or multi-use activities) is a potential data gap when it comes to seaweed cultivation given multi-use activities.

3.3.2. Workshop

The results of scenario discussions on food and feed hazards given the combination of seaweed cultivation at an offshore wind farm in the North Sea were gathered during a workshop. Table 3 outlines a cause-effect chain in the context of the scenarios presented to the experts. Hazards identified given the proposed scenarios included: (i) the release of oil, fuel, and chemicals; (ii) leaching of metals from equipment and the subsequent uptake of heavy metals in farmed seaweed; (iii) the presence of injured or dead birds contributing to the potential contamination of seaweed from bones, bacteria, fungi and viruses; and (iv) the growth of new species of algae, fungi, and bacteria, including toxins thereof from these organisms.

Moreover, experts deliberated on food and feed hazards, indicating that some hazards are relevant for single-use seaweed cultivation, meaning the combined use at an offshore wind farm does not necessarily present a new hazard given this context. Thereby, experts critically evaluated the hazards (Table A1). Of these, the uptake of iodine, plastics, and processing contaminants alongside other hazards in the food chain was noted as already present during single-use and therefore are not perceived as adding concerns given the multi-use scenario. Other concerns included the loss of seaweed from the platform as well as oil/gas emission and waste streams. These concerns were perceived as more economical and environmental issues, respectively. Finally, noise, shaking, or ultrasound given this multi-use scenario was assumed to have a negligible impact on the safety of seaweed for food and feed purposes.

3.4. Standards for multi-use at sea and identifying knowledge gaps

Results showed the need to harmonize multi-use terminology and to provide stakeholders guidance regarding best practices for multi-use at sea. This finding is further supported by the limited information available in the literature on multi-use at sea for food and feed purposes. The currently available public and private standards for food and feed
purposes can be implemented by stakeholders and contribute to the risk analysis paradigm. Fig. 1 shows an overview of food safety public and private standards and their potential application to multi-use at sea given seaweed cultivation at an offshore wind farm. It indicates how food and feed safety governance can be shaped to deal with concerns as given seaweed cultivation at an offshore wind farm. It indicates how private standards and their potential application to multi-use at sea can be implemented by stakeholders and contribute to the risk management of seaweed and seaweed products. Altogether, public standards are essential to be able to achieve multi-use at sea for food and feed purposes. National or local regulation may help to address pressing needs, e.g., for industry guidance on seaweed cultivation. Also, private standards such as FSSC 22000 and MSC/ASC are recommended for the food and marine sectors to consider when deciding which standards to implement for multi-use at sea.

Furthermore, experts identified knowledge gaps that need to be filled by new research given a limited understanding of multi-use at sea. Five knowledge gaps should be considered when critically evaluating food and feed safety hazards during the combined use of seaweed cultivation at offshore wind farms in the North Sea (Table 4). These were physical hazards (e.g., ropes, plastics, leaching metals), the effects of processing on seaweed, the contamination transfer rate to the seaweed, the effect of antifouling or protective coatings on structures near seaweed cultivation, as well as the seaweed type, adaptation, and farming practices thereof. These knowledge gaps warrant future research to be able to quantify the impact that an event has on the occurrence of a hazard. Such research results can better support the risk assessment process, thereby also helping to support future risk management and risk communication for food and marine policy. The urgency for new standards of seaweed production for food or feed purposes. Overall, the cultivation location, seaweed handling and processing, and seaweed testing are key points for attention by stakeholders, including policymakers, when evaluating the changes in the current regulation, as well as the seaweed type, adaptation, and farming practices thereof. These knowledge gaps warrant future research to be able to quantify the impact that an event has on the occurrence of a hazard. Such research results can better support the risk assessment process, thereby also helping to support future risk management and risk communication for food and marine policy.

4. Conclusions

Based on literature and expert elicitation, food and feed standards are available and can support multi-use at sea that involves seaweed production for food or feed purposes. Overall, the cultivation location, seaweed handling and processing, and seaweed testing are key points for attention by stakeholders, including policymakers, when evaluating the

| Stakeholder | Current or potential food safety issues relevant to seaweed and seaweed aquaculture | Current standards and regulations available to deal with these issues | Which issues are not covered? | What role does a new standard have for cultivated seaweed? |
|-------------|-----------------------------------------------------------------------------------|--------------------------------------------------------------------|-------------------------------|----------------------------------------------------------|
| Producer    | Location of cultivation                                                             | Organic certification (MSC/ASC)                                    | Iodine                        | Organic certification                                     |
|             | Handling and processing of seaweed                                                 | Sustainability certification                                       |                               | Location of cultivation                                   |
|             | Seaweed testing; heavy metals (cadmium), arsenic and iodine                         |                                                                    |                               | Applicability (i.e., feasibility) to apply standard      |
| Producer and Processor | Seaweed processing                              | HACCP                                                              | Direct reference to seaweed as food in the existing regulation | Templates of industry standards with a seaweed focus |
|             | Location of cultivation                                                             | FSSC 22000 or ISO 22000                                           | Challenges behind seaweed market development                | A sustainability aspect of seaweed cultivation         |
| Trader      | Contamination and traceability                                                      | HACCP (minimum)                                                   | Not much is missing            | MSC/ASC certificate for wild seaweed harvesters         |
|             | Analysis of product                                                                | ISO 22000                                                          | Limited demand for organic and sustainable certified seaweed | Certification has a value, but the current market is small |
|             | Heavy metals (mercury)                                                             | BRC                                                                |                               | Costs for certification are high (limitation)           |
| Business Innovator | Iodine                                      | National organic certification (similar to EU)                      | They have not encountered any issues with other heavy metals (mercury, cadmium, lead) | A common approach to farming and then a standard      |
|             | Arsenic                                                                            | ISO                                                                |                               |                                                          |
|             | Iodine                                                                             | BRC                                                                |                               |                                                          |
| Retailer    | Monitoring of water and environmental contamination                                | Food safety certificate                                            | Other contaminants             | Cooperation with primary producers                      |
|             | Arsenic                                                                            | BRC or International Food Standard                                | How seaweed is cultivated     | Sustainability and origin of growth standards          |
|             | Iodine                                                                             | GSFI                                                               |                               | Taste and healthiness                                   |
| Certification body | Location of cultivation                | EU General Food Law and labeling                                    | Practical tools to implement legislation and Codex           | Non-specific regulations allow the opportunity for interpretation, but a challenge for control |
|             | Heavy metals                                                                        | Novel Food Regulation                                              | Hygiene codes to make standards practical                     | Identify which seaweed belong                          |
|             | Arsenic                                                                            | ISO                                                                | Allergy concerns for seaweed consumption (given allergies to fish) | Help monitoring and transparency                        |
|             | Dioxins                                                                            | FSSC 22000                                                        |                              |                                                          |
|             | Pesticides                                                                         | GMP                                                                | Processing environment impact on potential cross-contamination of certain allergens |                                                          |
| National governmental authorities | Heavy metals                          | HACCP                                                              | Food consumption patterns   | The responsibility of the business to monitor product quality |
|             | Micro-organisms on the seaweed                                                     | National legislation                                               | The urgency for new standards | The national authorities should keep an eye on developments (monitor/supervise) |
|             | Marine biotoxins                                                                   | Codex                                                              |                               |                                                          |
|             | Minerals (iodine)                                                                  | BRC                                                                |                               |                                                          |
|             | Phytotoxins                                                                        |                                                                    |                               |                                                          |
|             | Concerns during storage (e.g., Salmonella)                                         |                                                                    |                               |                                                          |
|             | Pesticides assumed not to be used                                                  |                                                                    |                               |                                                          |
|             | Potential human-based risks (e.g., oil spill)                                       |                                                                    |                               |                                                          |
|             |                                                                                   |                                                                    |                               |                                                          |

Abbreviations: BRC, British Retail Consortium; EU, European Union; FSSC 22000, Food Safety System Certification 22000; GSFI, Global Food Safety Initiative; GMP, Good Manufacturing Practice; HACCP, Hazard Analysis and Critical Control Point; ISO 22000, International Organization for Standardization 22000; ISO, International Organization for Standardization; MSC/ASC, Marine Stewardship Council/Aquaculture Stewardship Council.
Table 3
Expert elicitation (workshop) on the cause and effect of food and feed hazards given the combination of seaweed cultivation at an offshore wind farm in the North Sea.

| Scenario                                                                 | Hazard                                                                 | Source/Cause                                                                 | Effect                                                                 |
|--------------------------------------------------------------------------|------------------------------------------------------------------------|----------------------------------------------------------------------------|------------------------------------------------------------------------|
| The collision of ships with other ships/foundations or a sinking vessel | The release of oil, fuel, and chemicals                                 | Results during a collision or from maintenance & harvesting boats           | Potential uptake of hazard into seaweed. If this occurs, the seaweed is potentially unsafe and cannot be sold/used for food/feed |
| The release of materials from substrates and equipment                    | Leaching of metals from coating material on foundations or ships and potential uptake of heavy metals by farmed seaweed | Results when materials from substrates and/or equipment break off, detach or release | Potential uptake of hazard into seaweed. If this occurs, the seaweed is potentially unsafe and cannot be sold/used for food/feed |
| Increased sea life/competition                                            | Injured and dead birds that cause potential contamination of seaweed due to bones, bacteria, fungi, and viruses | Results when birds collide with wind turbine rotor blades                   | Potential uptake of hazard into the seaweed. If this occurs, the seaweed is potentially unsafe and cannot be sold/used for food/feed |
| Integrated aquaculture                                                    | The growth of new species, algae, fungi, and bacteria as well as toxins from these organisms | Results from modifications in platform installations to permit multi-use    | If this occurs, there is an increased possibility for unsafe substances, competition with sea life, and a shift in potential food/feed safety hazards; seaweed is potentially unsafe and cannot be sold/used for food/feed |

a Experts did not further address the effect of climate change.

b The use of environmentally harmful components for antifouling is forbidden in Germany and the Netherlands.

Table 4
Expert elicitation (workshop) on the knowledge gaps and opportunities for future research given a multi-use at sea scenarios for seaweed cultivation at an offshore wind farm in the North Sea.

| Knowledge gap                                      | Explanation                                                                                                                                 |
|----------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| Physical hazards                                   | Relevant if materials from substrates and equipment released (e.g., ropes, plastics, leaching metals) into the surrounding environment. Dead animals can also affect the ecosystem, especially if they are present during cultivation. |
| Effect of processing                               | The rate that specific hazards transfer (e.g., in the water) to the seaweed and is taken up by the seaweed can influence the final exposure and thus any potential concerns for human health. |
| Contaminant transfer rate to crops                 | May influence genetic mutations or be of a concern for certain species.                                                                 |
| Effect of antifouling or protective coatings       | The needs for sustainable farming and rotating crops may be of a different need or concern depending on the seaweed species cultivated. The cultivation or harvesting practices, including the frequency thereof and machinery used, are relevant. Also, chemical weapon munition dumping may have occurred on or nearby the multi-use site and could alter the list of relevant hazards. |
| Seaweed type, adaption, and farming practices      |                                                                                                                                              |
potential for the combined use of seaweed cultivation at offshore wind farms in the North Sea. Although some food safety hazards may be more apparent for seaweed cultivation such as toxic metals (e.g., arsenic, cadmium) and iodine, others may become relevant when considering multi-use (e.g., allergens, PAHs, toxic metabolites).

Given the relatively new concept of multi-use at sea for seaweed food and feed purposes, the five identified knowledge gaps also point to potential hazards. These were physical hazards from equipment used, the effects of processing on seaweed, the contamination transfer rate to the seaweed, the effect of antifouling or protective coatings on structures near seaweed cultivation, and the seaweed type, adaptation, and farming practices thereof. The possible uptake of hazards into seaweed and bioavailability thereof is a research gap that needs to be addressed.

Public standards, FSSC 22000, and MSC/ASC are recommended for the sector, including policymakers, to consider when deciding which standards to implement for multi-use activities where seaweed is cultivated for food and purposes. Further guidance is needed here to be able to implement such standards and to support future management and regulation of marine activities. Harmonized, specific standards and implementation of these by the multiple stakeholders, including that of policymakers, will be required. Data gaps related to seaweed consumption patterns as well as the potential uptake of hazards into seaweed and bioavailability thereof warrant attention to be able to support the risk assessment process as well as future risk management and risk communication. Filling knowledge gaps on seaweed may help further support the commercial development of seaweed cultivation, especially given the more novel case of multi-use of seaweed and offshore wind farms. This case study provides an example of how to address seaweed food and feed safety in a multi-use scenario for the North Sea. We recommend performing additional case studies for other multi-use at sea scenarios.

CRediT authorship contribution statement

J.L. Banach: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Writing - original draft, Writing - review & editing. S.W.K. van den Burg: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Visualization, Writing - original draft, Writing - review & editing. H.J. van der Fels-Klerx: Conceptualization, Funding acquisition, Methodology, Project administration, Resources - writing review & editing.

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Appendix A. Supplementary data

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