Global Food Security 37 (2023) 100692

Contents lists available at ScienceDirect

Global Food Security

journal homepage: www.elsevier.com/locate/gfs

Knowledge needs in realising the full potential of seaweed for world food provisioning

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ARTICLE INFO

Keywords:
Food system approach
Food security
Value chain
Markets
Aquaculture
Seaweed

ABSTRACT

Seaweed has been receiving increasing attention as a novel food source worldwide. To optimally develop seaweed's food provisioning potential, the seaweed value chain requires further understanding. To this end, we used the Food System Approach to review the existing knowledge on seaweed as food source. We identified opportunities, constraints and knowledge needs relevant to fulfilling the potential of seaweed to contribute to food security. Thereby, we especially focus on optimizing and upscaling seaweed production and environmental sustainability. Our review shows that although progress has been made in solving technological issues in seaweed production, major knowledge gaps regarding social and economic factors remain. More attention to these issues can help realize the food potential of seaweed.

1. Introduction

The world population is predicted to reach 9.7 billion by 2050 (United Nations 2019). As a consequence, the availability of healthy and sustainably produced food is becoming a major issue. Based on the projected population growth, food demand is expected to rise by 70% by 2050, which is equivalent to an increase of 5.4 thousand million dry-matter tons of food per year (Forster and Radulovich 2015). Many scholars in the last 50 years focused on technological solutions needed to increase food production, while other strategies to increase food security received less attention in the literature (Tamburino et al., 2020). Humans have been fishing and farming for centuries, but more recently, several studies propose that seaweed farming could play a significant role in addressing or solving food security issues (Forster and Radulovich 2015).

Even though seaweed is being explored as a potential alternative to traditional arable crops and worldwide seaweed production has grown exponentially to 30 million tons per year in terms of fresh weight (approximately 3 million tons of dry matter per year) over the last two decades (Buschmann et al., 2017; Bjerregaard et al., 2016), seaweed farming is still in its infancy in most parts of the world. Exceptions are found in Asia where several countries play a dominant role in global seaweed production (FAO, 2020).

In Indonesia and the Philippines, the dominant species produced in 2012 were *Euchema* spp. (5.7 and 1.7 million tons produced per annum respectively, representing 27% and 8% of the total world seaweed production), mostly produced as a supplement for feed for cattle, while China produced a mix of species principally *Laminaria* spp. (4.8 million t; 23% of total), *Gracilaria* spp. (1.9 million t; 9% of total), *Undaria* spp. (1.7 million t; 8% of total) and *Porphyra* spp. (1.1 million t; 5% of total) for human production. *Laminaria* spp., commonly known as kelps, represents the most complex and largest brown alga and are considered one of the most important seaweed genera because of its high number of species, biomass, dominance, and economic significance (Baweja et al., 2016). This group is used as food additive (thickener and as a health supplement).

According to Duarte et al. (2021), seaweed aquaculture accounts for 51.3% of global mariculture production and the production is increasing at a rate of 6.2% per annum. Even so, to date, seaweed production only represents a small fraction, 0.3%, of the total global food production (Ferdouse et al., 2018) and is mostly used for direct human consumption in Asia (van den Burg, Dagevos, and Helmes 2019). Not all seaweed that

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https://doi.org/10.1016/j.gfs.2023.100692
Received 13 December 2021; Received in revised form 23 March 2023; Accepted 13 April 2023
Available online 15 May 2023

is produced, is used as human food; it is also used in cosmetics, pharmaceutical products, as feed for animals and as an ingredient for bioplastics (Selnes et al., 2021). Although we are aware of the relevant role of seaweed in other sectors and the potential effects this can have on its global use as food, we here solely focus on the role of seaweed in food security.

Bjerregaard et al. (2016) estimate that only 0.03% of the world's ocean surface would be needed to lift seaweed production from 30 to 500 million tons of dry weight a year, which could add 10% to the current world's supply of food. While there are uncertainties about the consequences of large-scale seaweed farming on the environment and nutrient depletion (Van der Meer and Jaap, 2020), the actual production is still much lower than the estimated potential global yield, and seaweed production is considered to represent a significant opportunity for meeting the increasing global food demand. Yet the question needs to be raised whether ecosystem engineering, technology or social and economic factors are the main constraints to seaweed achieving its potential (van den Burg et al., 2019).

Yield Gap Analysis (YGA) is a well-developed and commonly used approach to assess the difference between actual and potential production levels for arable crops (Sumberg 2012). Bridging the yield gap is used as a common approach to contribute to food provision, also concerning seaweed (Van Ittersum et al.,2013). Assessing yield potential for seaweed at a global level is more complicated compared to similar assessments for arable crops as this concept has not been used before with sea-grown crops. This comes from the facts that i) seaweed yield models are often only available for particular species or applicable to certain regions and ii) approaches that are available for assessing the potential primary production of seaweed are mainly based on biological and physical factors (Buschmann et al., 2017) and do not typically incorporate social, political, technological, and economic factors (van den Burg et al., 2019).

It seems evident that a more comprehensive approach is required to understand the potential of seaweed in the context of world food security, and many such approaches are available (Alarcon et al., 2021 Ingram 2011). We here chose the 'Food System Approach' (FSA), which is depicted in Fig. 1, as a framework for our analysis (van Berkum et al., 2018). This approach provides a comprehensive framework to identify potential constraints and enablers at different levels of the seaweed value chain. By identifying feedback mechanisms between the socio-economic and environmental factors along the value chain from production up to consumption, the FSA provides an integrated, interdisciplinary perspective of the value chain, allowing us to have a holistic assessment on the potential of seaweed for world food security (van Berkum et al., 2018).

1.1. Objective

Our objective was to explore the current knowledge in the form of scientific publications on the value chain of seaweed (activities, drivers, and outcomes) using the FSA to (1) identify principal enablers (opportunities) and constraints operating in the seaweed value chain and (2) identify remaining knowledge needs.

2. Methods

The current knowledge was assessed by reviewing the relevant literature published between 2010 and 2020. We conducted an exploratory bibliometric analysis (step 1) and an in-depth exploration of selected key scientific papers (step 2) as visualised in Fig. 2.

Step 1: Exploratory bibliometric analysis

The bibliometric analysis was used to explore the comparative amounts of research available targeting different sections of the seaweed food system and related to social, economic, and environmental aspects using search terms related to the FSA, as can be seen in Table 1.

An exploratory analysis was conducted, using a Boolean search strategy (Roe et al., 2015) to capture studies encompassing the entire bandwidth from primary production to consumption of seaweed. The search terms employed were kept broad to ensure maximum coverage and included variations combined with the term 'seaweed'. Synonyms were used in case the initial search led to no results or references that were beyond the scope of our focus. The literature search was limited to publications from the period 2010–2020. The broad scopes of the search terms used means that several technical publications of relevant scientific sub-disciplines were excluded. By focussing our search on the terms used in the FSA, we made a conscious demarcation of the scope and

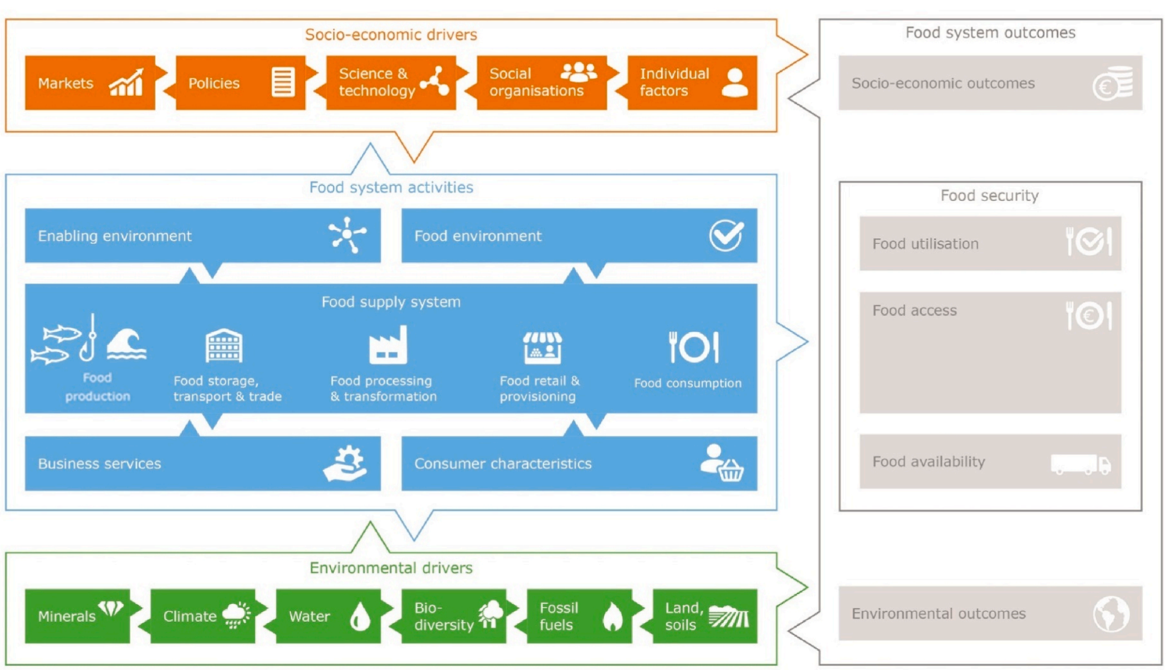

Fig. 1. Diagram of the relationships of the food system to its drivers (modification of the figure by van Berkum et al., 2018).

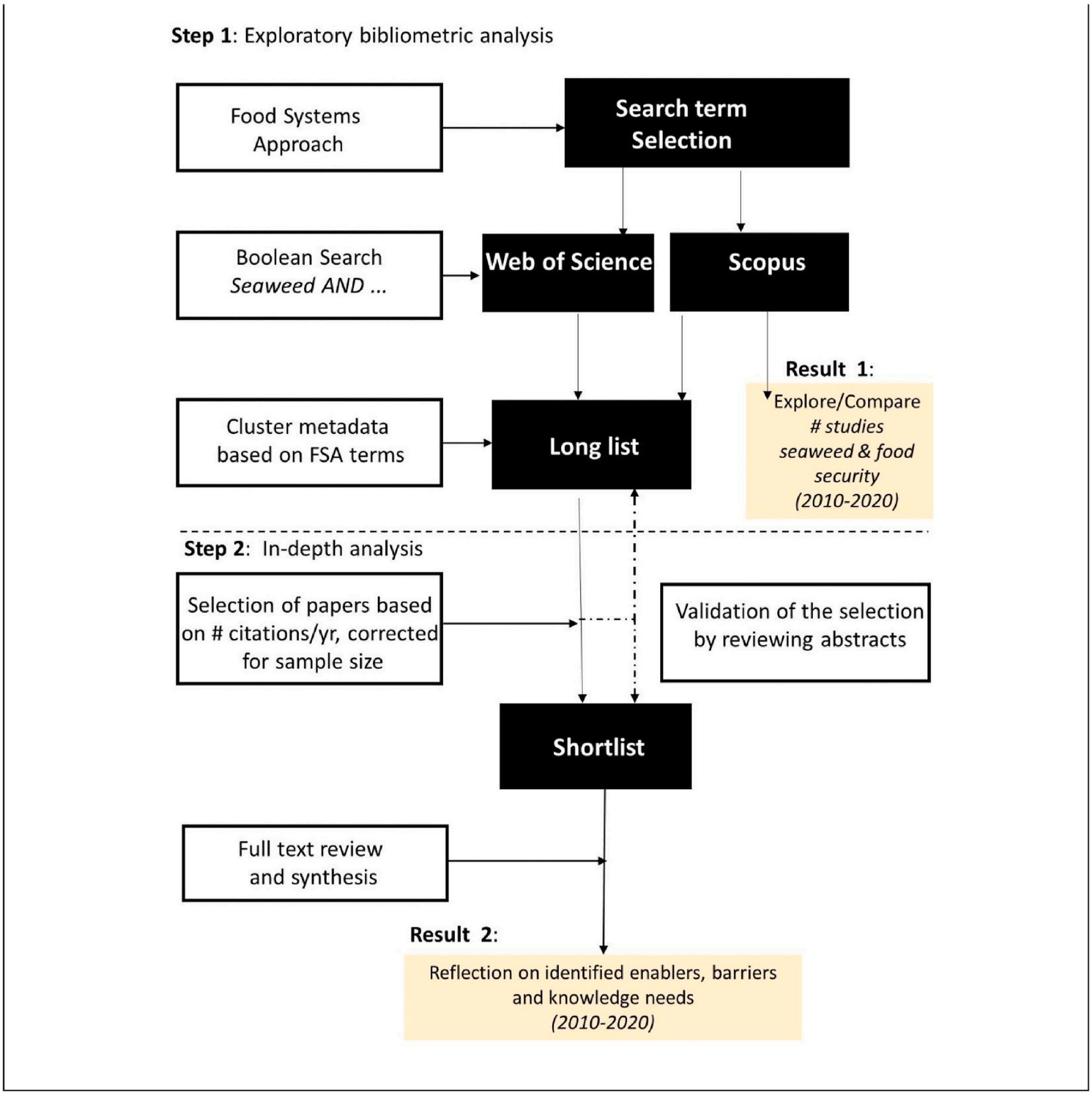

Fig. 2. Flow diagram of the research approach.

Table 1
Selected search terms and search term combinations, following Berkum et al. (2018).

	Boolean combination
Seaweed **AND**	*A1 search terms:* Production, Transport, Storage, Trade, Processing, Transformation[a], Retail, Provisioning, Consumption
Seaweed, *A1 search terms*, **AND**	Minerals, Climate, Water, Biodiversity, Fossil Fuels, Land, Markets, Policies, Science, Technology, social organizations, Governance, Behaviour
Seaweed **AND** synonyms transport	Moving, shipping, vessel, ship, conveyance, and transhipment.
Additional search terms transport	conditions, quality, requirements, quantity, degradation, value
Food Security **AND**	Aquaculture, Seaweed

[a] Transformation can either be understood as social change or chemical or physical change. In this research, the latter understanding of transformation is used.

intent of our review. Synonyms also exist for the search term ‘seaweed’ such as ‘macroalgae’ and ‘kelp’. We chose not to include these synonyms because ‘seaweed’ is the broadest term and therefore will result in the largest number of articles. We are aware that this limited our search results, however, we chose for this delineation to avoid including articles with a too technical nature.

The searches were performed in two different search engines: Scopus and Web of Science. Initially, the term “seaweed” was linked to each component or aspect of the value chain. In case this search strategy yielded irrelevant results, synonyms, and additional search terms were explored (see Table 1). The search terms “transport” and “behaviour” are examples that resulted in articles concerning the cell biology of seaweed (transport and behaviour of substances), and which clearly fell outside our scope of study and were therefore excluded from our study.

The search results (metadata) from both search engines were brought together in one Excel database, in Fig. 2 referred to as the ‘long list’. This long list of articles was used to compare the yearly number of publications regarding Food Security and those regarding seaweed value chains.

Table 2
Overview of used definitions of knowledge needs, opportunities, and constraints.

Knowledge needs: situations when opportunities or constraints do not yet have a convincing scientific theory despite conducted research. Knowledge needs may encompass more than research needs. For example, the necessary (scientific) knowledge may exist but is not or of limited availability to stakeholders (O'Toole and Coffey, 2013). For the shortlisted articles, we looked at whether additional research questions or knowledge needs were identified in the conclusions and recommendations.
Opportunities: situations or scientific insights that make it theoretically possible to achieve change or innovation towards increased sustainable provisioning of food, based on seaweed food chains.
Constraints: physical, technological, economical, or social conditions that limit the desired change (innovation) within a seaweed-based food system.

Step 2: In-depth analysis of enablers, constraints, and knowledge needs (qualitative research)

Citation ranking was used as a decision rule to delineate the number of retrieved publications (long list) for in-depth analysis. Frequently cited papers were therefore given more priority. Secondly, the sample size was considered, and approximately the same number of papers were included for each Boolean combination. In this way, both well and little-researched topics received equal attention. The first selection was based on bibliometric criteria to avoid unintentional bias and was validated by a review of the title and abstracts of search results. When knowledge needs, constraints or opportunities were mentioned in the title or abstract, those articles were selected for further in-depth reading. In this way, irrelevant papers were excluded for further analysis. Selecting articles for the shortlist was an iterative process. For example, references were crosschecked, and we frequently returned to the long list to select other articles for reading. Finally, we consulted with aquaculture experts in the food domain from Wageningen University and Research to review the shortlist. Moving towards the final analysis, the next step was to create summaries of the selected shortlist articles. These summaries described (1) why the article was selected, (2) how the search term connected to the FSA and (3) what opportunities, constraints, and knowledge needs (terms defined in Table 2) the article identified concerning seaweed food systems.

3. Results & discussion

3.1. Bibliometric data

Our initial searches showed that between 2010 and 2020, there was a linear increase in the number of scientific articles, books, and proceedings published related to one or more aspects of the seaweed food system. Fig. 3 shows the increase in the number of scientific articles about seaweed in comparison with those on food security. In 2010, 570 articles were identified that included seaweed as a keyword, whereas in 2020, a total of 1831 articles were identified. Regarding food security, 1237 articles were stored in Scopus in 2010 and 5141 in 2020. This shows that while the number of articles published on seaweed has more than tripled over the period, the number of articles on food security quadrupled over the same period. However, the combination of both seaweed and food security only accounts for a small number of articles with only 12 articles in 2020 (see Fig. 4).

Most articles for the different Boolean combinations were found in the category "production" whereas categories like "retail" and "provisioning" resulted in low numbers of articles. This indicates that those components received relatively lower scientific attention.

Secondly, we noted that a large share of the identified articles had a focus on environmental drivers and impacts of the seaweed food system. Environmental science-related keywords like minerals, climate, water, and technology resulted in many more publications than social science-oriented keywords like policies, social organizations, governance, and behaviour.

The keyword 'water' resulted in the highest number of articles for every part of the food system. This is not surprising, as water quality parameters and water content are, respectively, key criteria for seaweed growth and product quality.

3.2. Assessment of opportunities, constraints, and knowledge needs

Following the different categories addressed in the FSA, Table 3 shows the opportunities, constraints, and knowledge needs derived from the accessed literature from the shortlist (see Supplementary material 1).

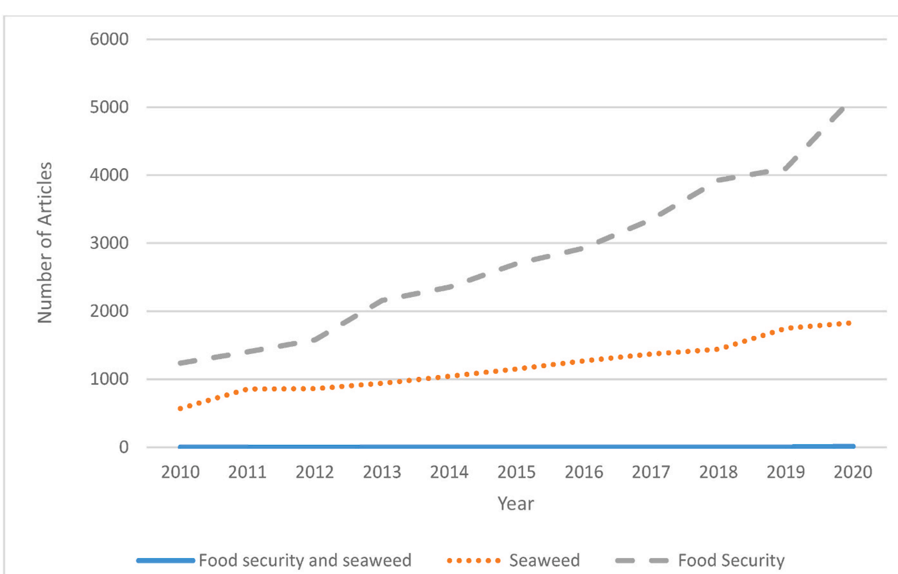

Fig. 3. Comparative trends in annual scientific output for the topics of 'food security and seaweed', 'seaweed' and 'food security' as assessed based on the annual number of articles appearing in peer-reviewed scientific journals for the period (2010–2020) as listed in Scopus.

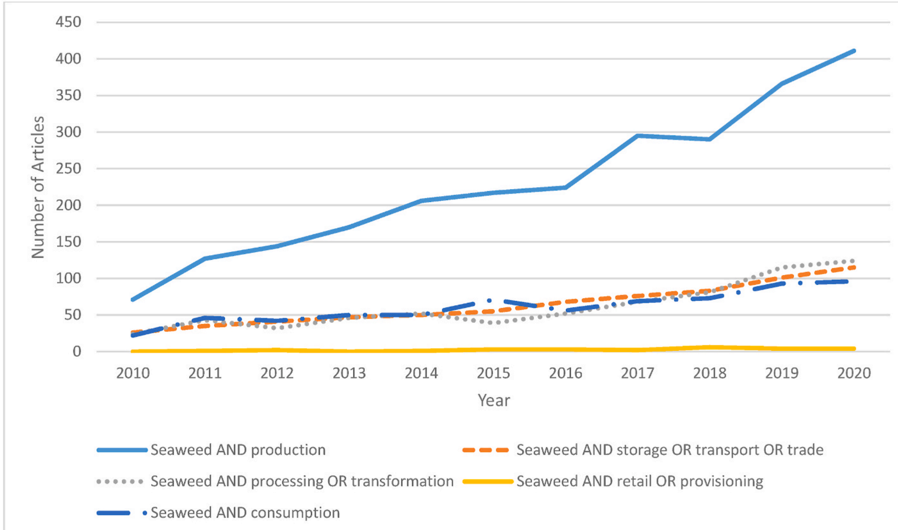

Fig. 4. The trend in the annual number of articles recovered in our searches of each area of the food system between 2010 and 2020. See supplementary material 2 for cumulative data.

Table 3
Synthesis of results: Constraints, opportunities and knowledge needs for each FSA activity concerning seaweed potential and implementation to improve food security.

Primary production		
Constraints	Opportunities	Knowledge needs
● Unstable prices for seaweed (Mariño et al., 2019). ● Weak organisation of seaweed farmers leads to a weak position in the global market (Muthalib et al., 2019). ● Weak organisation of seaweed farmers makes it difficult to make investments (Muthalib et al., 2019). ● Lack of incentives to increase seaweed quality because in practice, prices paid to producers rarely take quality of the product into account (Mariño et al., 2019). ● Seaweed is a promising product to use for biofuels (Lehahn and Alexander, 2016). This can claim areas where seaweed for food production could also have taken place. ● Recommendations are given for an offshore location of seaweed production, for it not to affect other ecosystem services (Cabral et al., 2016).	● Seaweed farming is an attractive alternative to fishing, it is less labour-intensive and more profitable (Mariño et al., 2019). ● Seaweed is suitable for feed (Bikker et al., 2016). ● Seaweed farms could be shelters and food sources for fish and invertebrate species (Dobson et al., 2020).	● How to increase economic feasibility of seaweed production tailored for different species and explore production combinations in aquaculture (Dobson et al., 2020). ● Lacking availability of best practices in seaweed farming (Rebours et al., 2014). ● Training/capacity building of farmers to become entrepreneurs in seaweed aquaculture (Rebours et al., 2014). ● Ecological response of seaweed on local (community) level and ecosystem level (Harley et al., 2012). ● Environmental impacts of seaweed cultivation and options to mitigate those (Harley et al., 2012). ● Benefits for biodiversity (e.g. Radulovich et al., 2015; Dobson et al., 2020). ● Impact of seasonality and variability in water quality on the biochemical composition of seaweed (Ramachandra and Deepthi, 2020). ● Models to help to understand the (global) potential of (integrated) seaweed production (Dobson et al., 2020; Fan et al., 2020). ● Multi-criteria analyses for location selection of seaweed production (Cabral et al., 2016). ● Assessment of impact/provision of seaweed cultivation on ecosystem services (Harley et al., 2012).
Storage & transport		
Constraints	Opportunities	Knowledge needs
● When seaweed is not properly stored, it loses its health benefits, texture, or quality (Choi et al., 2012). ● Drying procedures increase shelf time but may also negatively impact the chemical composition and antioxidant properties of seaweeds (Amorim and Chow, 2020). ● Thermal treatment in forced air tunnels as preservation method has high energy costs and can cause changes in the food matrix which often impact the product quality and might affect consumers' opinions (Pinheiro et al., 2019). ● Methane emissions during pre-processing and storage of seaweed (Herrmann et al., 2015).	● The potential of methane to be used as biofuel (Herrmann et al., 2015).	● Requirements for refrigerated storage are needed (Choi et al., 2012). ● Cost reduction potential concerning storage and pre-processing of seaweed (Nayyar and Skonberg 2018). ● Intraspecific differences in tolerance to abiotic stress, between cultivated and wild harvested seaweeds (Stévant et al., 2017).

Constraints	Opportunities	Knowledge needs
Trade		
● Limited market for seaweed food products.	● Potential role of seaweed as raw material for imitation caviar (Bronzi and Rosenthal 2014).	
Processing and transformation		
● Unpredictable fluctuations in nutritional value of seaweed (proteins, minerals, etc.) throughout the processing, e.g. resulting in a fluctuating sales (price) (Tiwari and Troy 2015). ● European law is unclear on the use of novel protein sources like seaweed (van der Spiegel et al., 2013).	● Seaweed processing can play a role in the absorption of CO_2 (Zhou et al., 2020).	● Changes in chemical composition throughout the processing of seaweed. ● The maintenance of the activity of seaweed after the manufacturing and cooking process (Lordan et al., 2011). ● Health risks related to seafood consumption are not clear yet (Lordan et al., 2011; Taylor et al., 2017). ● The behaviour of substances during the processing of seaweed into food and feed (van der Spiegel et al., 2013). ● Value chain studies (Gupta and Abu-Ghannam 2011). ● Legislation should be adjusted and clarified to introduce seaweed as a protein source to the European market (van der Spiegel et al., 2013).
Retail & provisioning		
● Missing, complex or not controllable regulations for biological safety seaweed.	● The market for seaweed does not necessarily associate with the condition of the natural environment in which the seaweed is cultivated (Wakamatsu et al., 2016).	
Consumption		
● Seaweed is often not part of diets in many places in the world (Nayyar and Skonberg 2018). ● Uncertainties about the nutritional value and overall health benefits (Wells and Brawley, 2017).	● Alternative protein source for meat/soy (Gómez-Ordóñez et al., 2010). ● Due to a increasing interest in minimally processed foods, opportunities for seaweeds as fresh vegetables grow (Nayyar and Skonberg 2018).	● Influence of consumer beliefs on the production of seaweed or other parts of the food system (Lucas et al., 2019). ● The availability of more knowledge makes consumers enlarge their seaweed consumption (Brayden et al. 2018).

3.2.1. Production

Multiple articles from the shortlist reflect on the location of seaweed cultivation (onshore or offshore) and what impact this could or did have on ecosystem services. For instance, a study in France by Cabral et al. (2016) recommended that seaweed culture can best be located further offshore to avoid affecting ecosystem services related to traditional oyster and mussel cultures. Rebours et al. (2014) showed that while many countries still rely on seaweed harvest from wild capture, seaweed aquaculture could be an alternative while ensuring sustainable livelihoods. Seaweed cultivation can be seen as an alternative to fishing because it is in general less labour-intensive, requires a relatively low capital investment and is more profitable (Neish 2013; WWF 2014; Limi et al., 2018; Mariño et al., 2019). However, prices can be unstable (Mariño et al., 2019), seaweed farmers generally lack proper organisation and representation (Muthalib et al., 2019) and people need training for seaweed aquaculture to be implemented in new regions (Rebours et al., 2014).

Seaweed cultivation has been reported to contribute to biodiversity (e.g., Radulovich et al., 2015), for instance by providing shelter and a source of food for fish and invertebrate species (Almanza and Buschmann 2013). However, in a case study from East Africa, seaweed farming led to a decrease in biodiversity caused by farmers deliberately removing seagrass (Unsworth et al., 2018). Additional risks are the potential introduction of diseases, parasites, and non-native species. These would need to be addressed by better biosecurity practices (Campbell et al., 2019). Mitigation measures on how to prevent negative ecological impacts have been identified as a main knowledge need (Harley et al., 2012; Campbell et al., 2019).

It is known that seaweed farming can provide ecosystem services (Buschmann et al., 2017) like oxygenation, the uptake of nutrients (Vásquez et al., 2014), and the uptake of carbon (Chung et al., 2011). These impacts are also receiving attention to assess if seaweed production can mitigate eutrophication and support the (long-term) sequestration of carbon (Manninen et al., 2016). On the other hand, Brodie et al. (2014) show that an increase in (dissolved) CO_2 concentrations can change the production conditions for marine organisms, including socio-economically important organisms. Some may profit but others might be negatively impacted. Global warming is predicted to threaten kelp forests in the southern hemisphere, and ocean acidification is predicted to reduce the coverage of maerl (non-jointed coralline red algae) habitat in the northern hemisphere (Brodie et al., 2014).

Dobson et al. (2020) point out that seaweed production in controlled land-based pond systems with other types of aquaculture (fish, snails) is promising, as it increases the total yield and it can aid in preventing excessive nutrient loading. Also, it can improve the water quality of the water systems that receive the aquaculture effluent. Research gaps regarding seaweed integration mainly lie in the economic feasibility and the benefits of different species combinations. For the latter, ecosystem models could help in studies to enhance economic feasibility (Dobson et al., 2020). For instance, Fan et al. (2020) developed a model that showed that combining oyster and seaweed production results in lower individual growth but causes a higher total production. Further development of such models can help understand the (global) potential of (integrated) seaweed production.

In addition, different seaweed species vary greatly in composition, with some seaweed species having primarily potential as a protein source and others primarily as a source of prebiotic compounds (Makkar et al., 2016). Bikker et al. (2016) also show that seaweed can be suitable as animal feed. They formulate research needs addressing extraction methods that help to reduce the high level of minerals and heavy metals, which can threaten animal and human health and feed safety (Taylor et al., 2017).

3.2.2. Storage

The storage requirements of seaweed depend on such factors as the period to be bridged between harvest and processing, climatic conditions, the quality of the harvested material, costs, energy needs and environmental impacts. Temporary storage of seaweed can take place at the seaweed farm, on ships, in the harbour, nearby the food processing industry or nearby shops. Pre-processing (e.g., drying) is often required before seaweed can be stored. Very little research has been done on these critical topics.

Drying procedures increase the shelf time but can also negatively impact the chemical composition and antioxidant properties of seaweeds (Amorim and Chow, 2020). We found some work aimed at extending the shelf life of intermediate and end products from seaweeds (del Olmo et al., 2020), maintaining nutritional value(s) during pre-processing and storage (e.g., Pinheiro et al., 2019; Nayyar and Skonberg 2018), maintaining non-nutritional values (e.g., raw material for biofuels, chemicals, medicines, or animal feed) (Sandbakken et al., 2018), finding the effect of storage on the agar yield and gelling characteristics (Lee et al., 2017), optimisation of ensiling time for seaweed to increase methane production (Herrmann et al., 2015), and on how to reduce methane production during drying of seaweeds (Regal et al., 2020). Stévant et al. (2017) explored the benefits and constraints of the storage of seaweed in seawater in terms of potential biomass reduction. They argue that further work is needed to quantify intraspecific differences in tolerance to abiotic stressors and between cultivated and wild seaweeds (Stévant et al., 2017, 14). Due to a growing interest in minimally processed foods, opportunities for the marketing of seaweeds as fresh vegetables are growing (Nayyar and Skonberg (2018) and call for further research on how storage temperature affects the quality of fresh seaweeds and on how to monitor seaweed quality during refrigerated storage.

3.2.3. Transport and trade

The articles selected here only pertain to the physical transport of seaweed and seaweed products from one place to another. Molecular transport studies are excluded.

Nurwandi et al. (2019) and Ghosh et al. (2015) use a value chain approach, comparable to FSA, to assess respectively the distribution pathways of seaweed from farm to warehouse as well as environmental impacts of different scenarios to transport liquid extracts of seaweeds to regional storage facilities. However, little attention was given to social-cultural factors. Other articles focus on specific case studies and topics, like the trade of seaweed for aquaria (Vranken et al., 2018) or the potential role of seaweed as a raw material for the imitation of caviar (Bronzi and Rosenthal 2014).

3.2.4. Processing and transformation

We assessed a number of papers focussing on the use of seaweed as food additives in our diets (e.g., Chattopadhyay et al., 2010). It is argued that seaweeds can play a crucial role in fulfilling the consumers' demand for healthy and nutritious food (Lordan et al., 2011). Lordan et al. (2011) discuss marine-based ingredients (nutraceuticals), amongst which seaweeds, as attractive options for the food industry because of their wide availability, relative cost-effectiveness and their specific biological activity that has a positive effect on treating several diseases. More research needs to be done on the exact composition of marine extracts to find out whether the biological advantages are maintained after the cooking process (Lordan et al., 2011). Seaweed is a source of abundant dietary fibre (Elleuch et al., 2011) and can therefore be a functional ingredient of many different types of healthy food products.

Seaweed is also mentioned as a promising new protein source that could (partly) replace animal-derived proteins. However, European legislation regarding the use of these protein sources is unclear. While their technological and processing characteristics have been abundantly studied, not much investigation has been done on possible food safety hazards. Before market introduction of seaweed-based food products much more work is needed on the behaviour and impact of these novel products in the environment, during processing and transportation of substances to both food and feed. None of this is yet properly addressed in European legislation (van der Spiegel, Noordam, and van der Fels-Klerx 2013).

3.2.5. Retail and consumption

Lucas et al. (2019) show that it may help to increase consumers' knowledge of seaweed products and recipes to increase seaweed consumption. Also, the application of health labels can contribute to an increase in seaweed consumption. Several of the analyzed studies link seaweed explicitly to health benefits for consumers, in particular as dietary mineral supplementation (e.g., Circuncisão et al., 2018). Circuncisão et al. (2018) also conclude that it is important to establish specific regulations on European edible seaweeds. Furthermore, seafood, including seaweed, can contain excessive concentrations of arsenic. Arsenic from seafood is considered to be organic – and therefore non-toxic - but Taylor et al. (2017) argue that more research is needed on the effects of arsenic concentrations in seafood and human consumption.

4. Conclusions

A first step towards setting priorities is to understand constraints and enablers for upscaling existing and developing new innovative seaweed value chains while exploring which knowledge needs will support setting priorities for research, food policies, capacity building and social-cultural changes that can allow seaweed products to conquer a place on our food shelves. What is striking is that the literature analyzed does not explicitly mentions enablers that can accelerate the innovation process, while identifying those enablers are essential to increase the economic feasibility. However, we are also convinced that the research community is aware of the essential role of enablers. Social sciences can be of added value at this point, especially when using FSAs. The identified knowledge needs focus on a) optimizing, b) upscaling issues and c) making the production chain more sustainable (Table 3). We identified knowledge needs regarding the optimal use and valorisation of the many discovered biological qualities of seaweed. The plant's physiological mechanisms are not yet completely understood, making it difficult to guarantee a continuous quality of the seaweed product in question for all parts of the food system. The FSA makes it possible to consider the preconditions imposed on the quality of the seaweed products in each part of the production chain in research.

Opportunities and constraints often go hand in hand in research. Seaweed was mentioned as a resource for food, feed and (bio)fuel (opportunity). For many of these new products, the value chain and the markets still need to be developed (constraint).

In the introduction, we indicated that global and regional assessments try to identify the untapped potential of seaweed cultivation in terms of suitable production areas at sea and on land or production increase per hectare based on environmental criteria. Many scholars acknowledge the uncertainties in these assessments and propose alternative modelling strategies (Van Oort et al., 2022).

Our review shows that seaweed food products are scientifically proven beneficial for human health. Therefore, we conclude that the ultimate contribution of seaweed to food security can be substantial because of its nutritional value. However, there are knowledge needs to be addressed before these healthy seaweed products are ready for market introduction. Being able to offer seaweed products of constant quality regardless of production conditions is an example of a scientific knowledge need. The question of how to get potential entrepreneurs and consumers excited about respectively producing and eating seaweed is an example of a societal constraint that needs to be addressed by further research.

There are some social scientific articles included in this study, like Mariño et al. (2019) who state that seaweed products (also non-food) can generate income for people who are involved in the value chain (opportunity), which can indirectly increase food security. We have not found any literature that confirmed this statement with empirical data.

Legislation and policies were mentioned as both an enabler and constraint. In our view, regional policies can play a role as enablers for production and regulators for sustainability. It is worthwhile to explore with the FSA how these two roles of policies can create synergies instead of inconsistencies in legislation, in particular for seaweed food products that are not yet market-ready. Usually, policies follow the latest developments in the market. With emerging markets for seaweed food products this can be reversed, creating the policy while the market sorts itself out. This might give more stability and long-term vision for the seaweed market.

A major area of work is to make consumers more familiar with seaweed products. Especially outside Asia there is an opportunity to increase the role of seaweed in diets. For this to happen, the benefits of seaweed food products compared to already-present alternatives need to become more evident to consumers and consumers need to be introduced to a wider range of seaweed products. In this, the new bioeconomy trend whereby producers and consumers are increasingly becoming and behaving more environmentally conscious offers new perspectives (Weiss et al., 2020).

The reviewed literature illustrates that science and industry are making progress in making the extraction of protein from seaweeds both technically and economically feasible. Seaweed could therefore be an interesting and sustainable alternative to meat or soy. However, solving the remaining technological knowledge needs like health benefits and the nutritious value of seaweed, is not enough to turn seaweed into a marketable alternative. In addition, social changes are needed to alter consumer behaviour. Furthermore, it is difficult to predict how the market for seaweed products will develop. The drivers behind these forces in the food system can also influence each other in unforeseen ways. An important precondition for market growth is that the involved entrepreneurs, from seaweed farmer to retailer, must better organise themselves in such a way that more seaweed can be produced, and the quality of seaweed can improve.

5. Recommendations

(1) Improve the social and economic dimensions in food system research

The results illustrate that knowledge needs in food systems must be addressed with both experimental research and organizational change along the whole seaweed chain. The actors involved also need additional skills, know-how, and improved access to knowledge, technology, research, and financial resources. While the producers of seaweed products have reasons to behave as they currently do, it is recommended to explore financial arrangements that may facilitate behaviour leading to more seaweed use in all parts of the food value chain. More attention is needed to communication, marketing strategies and product development to encourage consumers to include seaweed products in their diet and to encourage enterprises to introduce seaweed products all around the world. Finally, strategic choices in order to enhance the potential of seaweed for food provisioning are different for mature, existing seaweed production chains and markets compared to emerging markets for which the production chain is yet to be developed. In countries with existing seaweed production, enablers will, for example, be needed to convince seaweed farmers to adapt their business, while in countries where seaweed markets are emerging, entrepreneurs must be convinced and enabled to embark on a new adventure. A strategic choice is for example: should all components of the seaweed food system be located in a single country or region, or be the food provisioning potential from regional specialization? The answer to this question is undoubtedly dependent on local social, economic, environmental conditions. The FSA approach is a promising tool with which to conduct such an analysis. Consumers and food manufacturers will need to be taken be involved in every step of the way in the evolving food system for seaweed.

(2) Shift focus from yield gap to productivity gap

Bridging the gap between the potential yield per hectare and actual yield by optimizing seaweed cultivation is a challenge as primary production at sea is already very efficient (van der Meer et al., 2020). When looking for new locations for commercial seaweed production it is important to assess the environmental and economic preconditions for seaweed cultivation. The highest achievable production is not always sustainable if other societal challenges, such as declining biodiversity or other human activities are considered. In addition, available economic capital and social support must also be considered when identifying areas at sea that are suitable for seaweed cultivation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors would like to acknowledge funding from the Wageningen University & Research ‘Food Security and Valuing Water programme’ (KB-35-007-002) and Circular and Climate Neutral’ programme’ (KB-34-007-010), which are both supported by the Dutch Ministry of Agriculture, Nature and Food Security.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gfs.2023.100692.

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