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Using quantitative storytelling to identify constraints in resource supply

The case of brown seaweed

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Abstract

Seaweed is increasingly considered a promising resource to produce high-value products such as bioplastics due to potential environmental benefits such as carbon uptake and no land-use change. However, the environmental assessment of emerging technologies for producing bioplastic from seaweed remains challenging due to the difficulties in modeling future seaweed supply and demand. Within the consequential approach to life cycle assessment, an increase in demand for seaweed is met by the marginal suppliers in the market: those that are not constrained in their capacity to increase supply in response to an increase in demand. Current methods to identify marginal suppliers are however based on quantitative information and do not consider qualitative aspects and uncertainties inherent in the study of emerging technologies. This study, therefore, proposes and tests the use of quantitative storytelling to identify marginal suppliers. The results show that there are two main groups of countries that are expected to be the marginal suppliers of brown seaweed for different reasons. Asian countries are currently the main brown seaweed suppliers and are expected to keep increasing and be marginal suppliers in the future. However, these countries have well-established brown seaweed aquaculture and their growth is expected to be steady. On the other hand, brown seaweed suppliers in Northern Europe and North America are still emerging but are expected to grow faster in the future due to their production capacity and technological development.

KEYWORDS
bioplastic, blue bioeconomy, consequential life cycle assessment, industrial ecology, macroalgae, marginal suppliers

1 | INTRODUCTION

The concept of blue bioeconomy, defined as an economy based on aquatic renewable bioresources, is gaining momentum and seaweed is among the most important feedstocks (Addamo et al., 2021). Seaweed aquaculture can potentially bring environmental benefits such as providing ecosystem

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services (Thomsen & Zhang, 2020), contributing to global carbon, oxygen, and nutrient cycles (Brodie et al., 2014; Seghetta et al., 2016; Visch et al., 2020) or reducing eutrophication (Xiao et al., 2017). Additionally, seaweed does not compete with other land-use resources and, hence, there is no land-use change, use of fertilizers, pesticides, or freshwater involved in seaweed aquaculture, as in other bioresources (Duarte et al., 2017, 2021; Giercksky & Doumeizel, 2020; Hasselström et al., 2020).

The global seaweed production was 35.7 million tons of wet biomass in 2019, with human consumption being the main market (Cai et al., 2021), which poses a potential limit to how much of existing seaweed supply can be used for the production of bioplastic. Brown seaweed production grows annually by approximately 11%, from 13.000 tons in 1950 to 17.6 million tons in 2021(Cai et al., 2021). Currently, 96.5% of the total global production of brown seaweed comes from aquaculture (FAO, 2023), while in Europe it comes primarily from wild harvesting (Araújo et al., 2021; Stanley et al., 2019). There is a recent increasing interest in seaweed aquaculture (Peteiro et al., 2016), especially in Europe (Bak et al., 2018; van den Burg et al., 2016), to meet the future increase in demand (Stévant et al., 2017).

In recent years, the use of seaweed has been assessed as a potential source to produce bioplastic (Carina et al., 2021; Lim et al., 2021; Sudhakar et al., 2021; Zanchetta et al., 2021; Zhang et al., 2019). In the transition to a bio-based economy, bioplastics are a potential solution to reduce the dependence and extraction of fossil resources (Bishop et al., 2021; Spierling et al., 2018). First-generation and second-generation bioplastics, made from edible crops and plants and agro-industrial waste, respectively, require intensive use of land and water, contributing to direct and indirect land-use change (Brizga et al., 2020; Ita-Nagy et al., 2020). The use of food crops for bioplastic production is questionable due to the risk of creating competition with the food market, which could lead to higher food prices and food insecurity. Third-generation bioplastics are still under development and relate to the use of living organisms to produce plastics not using land resources (Brizga et al., 2020), including seaweed. Seaweed-based bioplastics potentially offer a more sustainable alternative compared to other type of bioplastics, as seaweed is a renewable resource that does not require arable land for its supply.

Novel brown seaweed-based bioplastic is considered an emerging technology from a life cycle assessment (LCA) perspective. If this emerging technology is implemented, it is important to understand which suppliers will respond to a future increase in demand for seaweed, to anticipate the impact that will be induced by such demand (Bergerson et al., 2020; Blanco et al., 2020; van der Giesen et al., 2020). In a consequential LCA approach, those suppliers are referred to as marginal suppliers (Consequential-LCA, 2020; Pizzol & Scotti, 2017; Weidema et al., 1999). In theory, this identification is intended to be an analysis of the possible constraints to increasing the supply of a specific product. In practice, however, the methods rely on a combination of assumptions and modeling, for example, regression analysis and trade statistics (Buyle et al., 2018; Sacchi, 2018; Weidema et al., 1999). These quantitative methods have mainly been applied to established technologies with a relatively large amount of data available, fully addressing the challenges related to the assessment of emerging technologies, including data scarcity and uncertainties in forecasting future scenarios.

Current methods to identify marginal suppliers do not apply well to the case of brown seaweed because data on brown seaweed supply is scarce and unreliable. There are two main statistic sources for seaweed production: The Joint Research Centre (JRC, 2021) for brown seaweed statistics in Europe and the Food and Agriculture Organization (FAO, 2023) for global statistics. However, since countries have no legal requirements to publish precise data, the available data on brown seaweed is, therefore, incomplete (Araújo et al., 2021). Studies that attempt to make future projections on brown seaweed supply are qualitative or based on simple extrapolations (Duarte et al., 2021). While qualitative information can serve as a starting point in identifying marginal suppliers, many constraints to upscale the production can only be identified qualitatively, for example, the current state of emerging trends in optimal growth conditions, including locations and cultivation designs, regulatory regime shift, and technological development.

Summing up, a better framework to identify marginal suppliers for emerging technologies is needed, that can handle the intrinsic uncertainty, and combine both quantitative and qualitative information on existing and emerging development of the brown seaweed production and brown seaweed-based bioplastic market.

In this context, the objective of this study is to propose the use of quantitative storytelling (QST), a mixed-methods approach proposed by Saltelli and Giampietro (2017) for supporting policy and decision-making in the sustainability domain, to identify marginal suppliers of brown seaweed. We investigate the global brown seaweed market and determine the marginal mix of suppliers to use in consequential LCA. The marginal mix represents the relative share of suppliers with a positive growth rate in the total supply. Combining qualitative and quantitative information, QST is used to investigate the current market trends and the consequences of increasing demand for brown seaweed to produce bioplastic. We also evaluate challenges in upscaling reflecting on the marginal supply, including production capacity, technology development, regulatory constraints, and the market niche for brown seaweed bioplastic. This research contributes with new methodological insights on the identification of marginal suppliers of emerging technologies, where uncertainty and qualitative information play an important role.

2 | METHODS

The QST approach has been recently proposed by Saltelli and Giampietro (2017) as a complementary approach to traditional evidence-based policy. QST explores systematically the multiplicity of frames that are potentially legitimate in a scientific study. It assumes that in an interconnected

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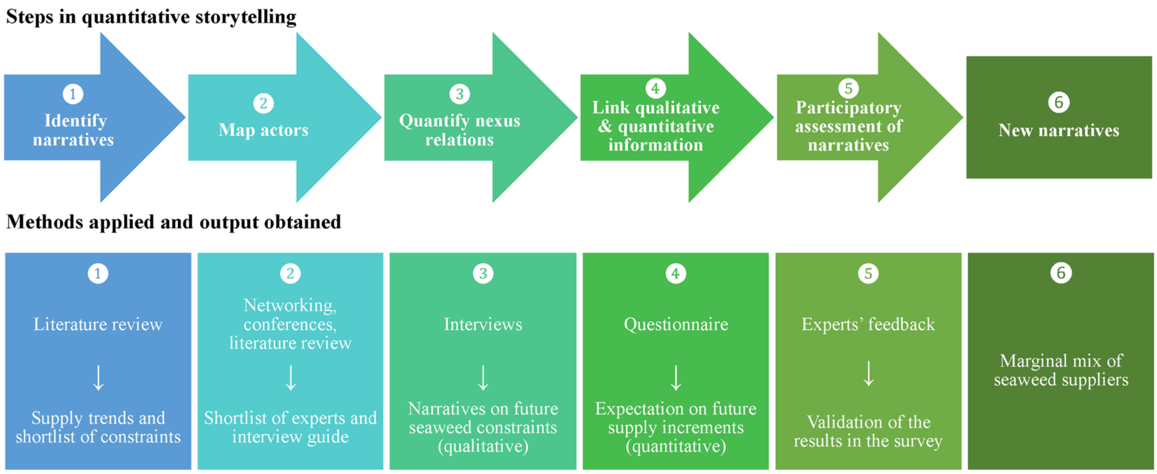

FIGURE 1 Steps in quantitative storytelling as described in Cabello et al. (2021) and corresponding methods applied in this study. [Correction added on 12 Oct 2023, after first online publication: An early version of Figure 1 was erroneously published. This has been replaced with the final version which includes all 6 steps.]

society, multiple frameworks and worldviews are legitimately upheld by different entities and social actors (Saltelli & Giampietro, 2017). More recently, Cabello et al. (2021) proposed a six-step procedure to further operationalize QST. In this study, we adapted the procedure proposed by Cabello and co-workers to our case (Figure 1) and followed the six steps to identify brown seaweed marginal suppliers: (1) Map actors, (2) Identify narratives, (3) Quantify nexus relations, (4) Link qualitative and quantitative information, (5) Participatory assessment of narratives, and (6) New narratives.

2.1 | Step 1: Identify narratives

A review of existing literature was first conducted to shortlist typical constraints to supply that are often considered in consequential LCA studies. Initially, we focused on the LCA literature and used various Boolean combinations of the keywords: "*Consequential*," "*LCA*," "*Marginal suppliers*," and "*Constraint*" to identify scientific articles performing marginal suppliers' identification in general, then described the type of data used in such studies, the processing applied to the data, the constraints considered, and the research gaps. Two main sources were particularly relevant: Buyle et al. (2018) provided an overview of existing consequential studies and Weidema et al. (2009) introduced a series of possible constraints. Based on these, other relevant references were identified (Buyle et al., 2018; Ekvall & Weidema, 2004; Frischknecht & Stucki, 2010; Ghose et al., 2017; Lund et al., 2010; Pizzol & Scotti, 2017; Sacchi, 2018; Schmidt, 2008; Schmidt & de Rosa, 2020; Schmidt & Weidema, 2008; Thonemann & Pizzol, 2019; Weidema et al., 1999, 2009; Wernet et al., 2016). The identified scientific articles were organized in a table, including the main method used to identify marginal suppliers and the considered constraints. The literature review table is provided in Supporting Information S1. As a result of this literature review, we concluded that the constraints most typically considered in consequential LCA studies are *geographical market delimitation; market trend*; *most sensitive suppliers to change*; *production capacity;* and *technology development*.

We focused on the literature on brown seaweed and retrieved information on the global state of seaweed harvesting and farming, growing conditions, production methods, aquaculture, spatial planning, and economic feasibility. Statistics on brown seaweed suppliers from FAO and JRC were also accessed. Seaweed cultivations appear to be geographically constrained by environmental conditions and country-specific regulations. As a result, two more constraints were included to identify brown seaweed marginal suppliers: *policies and regulatory constraints* and *natural constraints*. Even if the constraints were not explicitly considered in current quantitative consequential studies to calculate the marginal mix, we evaluated these as necessary to understand the brown seaweed market and its future development.

Summarizing the results of the review on marginal suppliers and brown seaweed, the identified constraints were grouped into four main constraints based on the information they provided. *Market trends* and *most sensitive suppliers to change* were grouped under *geographical market delimitation* considering that they provided the same information regarding the current status and future projections of the global brown seaweed supply market. *Natural constraints* and *production capacity* were grouped as they both give information about productivity. The last constraint was *technological development*, which included upscaling. These constraints can potentially condition the future brown seaweed supply.

- *Geographical market delimitation*: Market trends, market boundaries, predominant brown seaweed suppliers, and market prospects.
- *Policies and regulatory constraints*: Regulations constraining the brown seaweed trade and market.

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- *Natural constraints and production capacity*: Productive brown seaweed species and environmental parameters and techniques to increase productivity.
- *Technological development and upscaling*: Technological prospects to upscale brown seaweed production.

The four constraints were used as a starting point to design the interviews with experts in the seaweed domain (cf. *Step 3: Quantify nexus relations*).

2.2 | Step 2: Map actors

Experts in brown seaweed were identified using information from the literature, participation in conferences on seaweed science, and contacts in the authors' research network. The list of experts included phycologists, experts in seaweed aquaculture, the Asian and European seaweed market, seaweed farmers and harvesters, and experts with knowledge of bioplastics. In the selection of the interview sample, experts from different countries and both academia and the private sector were targeted.

An interview guide was prepared (cf. Supporting Information S2), organized into four blocks of questions: one block for each constraint plus a fifth block of questions to focus on the use of seaweed for producing bioplastic. The questions about market delimitation and geographical market boundaries included questions about China's success in the past, present, and future; other potentially predominant future suppliers; and the prospects of the brown seaweed supply. The respondents were asked to reflect on whether brown seaweed is a local or global market and the limitations and possibilities of trading seaweed. The productivity, environmental, and technical parameters conditioning the seaweed growth were also explored. The questions on technological development explored upscaling the production in the future, technological development, and learnings from predominant suppliers. Finally, the questions on seaweed-based bioplastic were about the potential species for bioplastic production, the importance of the proximity of bioplastic production facilities to the seaweed farms and competition with the current main target markets.

2.3 | Step 3: Quantify nexus relations

Using the interview guide and the shortlisted experts, interviews were conducted to obtain the most relevant qualitative information to identify the main brown seaweed suppliers. A total of 11 experts with different expertise and nationalities were interviewed: six academics, three seaweed farmers, a senior researcher, and a policy maker. Interviewees were from Denmark, Norway, Sweden, the Faroe Islands, France, the Netherlands, the United Kingdom, Portugal, Korea, and China. The interviews were held online and recorded with the consent of the interviewees. The interviews were then transcribed and analyzed using a matrix approach. The first column included all quotes from the interviews and the first row included the interview questions. In each quote/question intersection cell, a "condensed meaning" of the quote (e.g., the most relevant keywords) were then extracted and the keywords were written under their corresponding question. In the case of having quotes corresponding to various questions, they were coded under different questions. With this method, we could filter the answers to each question. The answers were summarized systematically and key quotes with exemplary or recurring information were extracted (cf. Supporting Information S3). In the case of having similar quotes providing the same information, only the quotes with more complete information were used in the summary of the interview. Afterwards, we summarized the answers based on the constraints (cf. Section 3). The result was a narrative about each future constraint to brown seaweed production.

2.4 | Step 4: Link qualitative and quantitative relations

LCA is a quantitative assessment tool and quantitative information is needed in the modeling process. In this step, the interviewees were contacted in a second round for a short expert elicitation questionnaire. Five of them were willing to contribute and thought could provide meaningful answers. The aim was to obtain quantitative projection estimates of production increments to define a marginal mix of seaweed suppliers needed in consequential LCA modeling.

All the countries mentioned during the interviews as possible future brown seaweed suppliers were listed in the questionnaire. First, the experts were asked to select from the list of countries the most competitive suppliers in the middle–long term: between 2025 and 2035. Afterwards, they were asked to estimate the growth rate in the brown seaweed supply from each of the selected countries. The following questions were used to estimate the marginal mix of brown seaweed suppliers in 2025, 2030, and 2035. The last question referred to the expected market shares of brown seaweed for bioplastic in 2025, 2030, and 2035. The template of the expert elicitation questionnaire with the specific questions and answers options can be found in Supporting Information S4.

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2.5 | Step 5: Participatory assessment of narratives

To validate the results obtained in Step 4, a validation questionnaire was conducted with the experts who participated in the interview (Step 3) and the expert elicitation questionnaire (Step 4). In addition, a broader group of experts was contacted in person at a conference on seaweed science to obtain different and more representative perspectives. The aim of this validation questionnaire was to assess the level of agreement of the experts with the findings about marginal suppliers. In the validation questionnaire, the results on the marginal suppliers were presented as a starting point for the questions. The experts were asked to express to what extend these results matched their expectations, on a five-point Likert scale ranging from "Very poor match" to "Excellent match." The experts were also asked a follow-up question to identify the variable that they found most uncertain. The three variables provided as options were: the listed countries, the percentage of shares, and the scenario trends. Both multiple-choice questions were accompanied by an open-text question box giving the opportunity to elaborate on the provided answer. The validation questionnaire template and the answers are presented in Supporting Information S5.

2.6 | Step 6: New narratives

We analyzed quantitatively the results of the expert elicitation questionnaire. The countries that had been selected by at least 60% of the respondents were considered and calculated their average estimated growth rate across respondents. It was calculated as in Equation (1):

$$\text{Average annual growth rate} = \frac{\text{Growth rate given by respondants}}{\text{No. respondents}} \tag{1}$$

Based on the obtained average growth rates, we then derived a marginal mix by calculating the percentage of each supplier to the total supply. In the expert elicitation questionnaire, the experts were asked to directly provide their estimate of the marginal mix (cf. Supporting information S4). Equation (2) was then used to calculate the marginal mix:

$$\text{Marginal mix } (\%) = \frac{\sum \text{Respondent marginal mix } (\%)}{\text{No. respondents}} \tag{2}$$

Respondent marginal mix is the marginal mix estimated by each respondent in the questionnaire. Following these steps, the marginal mix of marginal suppliers was obtained. This marginal mix will form the basis for consequential LCA of a transition into seaweed-based bioplastic.

Finally, the average market share for bioplastics was calculated. Like the marginal mix, the experts were asked to estimate the annual share of the total production of brown seaweed supply for bioplastic. We calculated the average market share for bioplastic according to Equation (3) to calculate the average market share for bioplastics:

$$\text{Average market share for bioplastics } (\%) = \frac{\sum \text{Respondent market share } (\%)}{\text{No. respondents}} \tag{3}$$

Respondent market share is the expected market share for bioplastic from the total brown seaweed production volumes. All data and calculations are provided in Supporting Information S6.

3 | RESULTS

3.1 | Geographical market delimitation

China is the main global brown seaweed supplier. China's success can be explained due to its long tradition cultivating and consuming seaweed, knowledge of seaweed aquaculture and breeding species to obtain high yields, large demand, and an established market. Most experts agreed that Chinese seaweed producers will be front-runners at least in the next decade and even if European production is expected to grow, it will not overtake Asian production volumes.

The interviewees made a high-growth projection of brown seaweed production. The main driver of the expected increase in brown seaweed demand is an increasing global interest in using seaweed for different applications and the need for new resources in the coming years, bioplastic being one potential new market. Another driver to cultivating brown seaweed mentioned by experts was the environmental benefits of seaweed cultivation, including ecosystem services and carbon capture. Technological development in brown seaweed aquaculture was mentioned as another driver, including selective breeding and mechanizing the production process to optimize productivity and area utilization.

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When interviewees were asked about brown seaweed suppliers in the future, all of them agreed with the potential of Norway to become a predominant brown seaweed supplier due to its favorable environmental conditions and technological development. Another factor is Norway's aquaculture and offshore technology industries which can support the upscaling and industrialization of seaweed cultivation. Atlantic European countries and islands were the most repeated potential future suppliers by experts. These included the Faroe Islands, Iceland, Greenland, Ireland, the United Kingdom, the Netherlands, Belgium, France, Sweden, Denmark, Portugal, and Spain. Other countries outside Europe were considered: The United States, Canada, Chile, Australia, Korea, and Japan. A few experts named New Zealand, Namibia, and Kenya.

3.2 | Policies and regulatory constraints

Experts agreed that seaweed is a global free market and there are no regulatory limitations for the global seaweed trade and dry seaweed can easily be transported. Some experts mentioned that even if seaweed can be traded globally, regulations are needed to ensure the quality of the seaweed.

Buying local or imported seaweed is market dependent. Asian countries already have a large internal brown seaweed demand for food applications and the volumes of seaweed that they export are small. In Europe, consumers are more inclined to buy locally, mainly for food safety and sustainability reasons. The international trade of non-food applications is less constrained than the food and feed market, and it is an increasing market. According to the interviewees, seaweed origin is less significant for non-food uses.

In some countries, obtaining permits to cultivate seaweed is another regulatory constraint. Moreover, in most countries, it is required to cultivate native species. The regulations to cultivate seaweed in Asia are more flexible.

3.3 | Natural constraints and production capacity

To upscale brown seaweed production, various aspects regarding natural constraints and production capacity need to be consider. First, the selection of the most productive species. Different species are cultivated globally, but *Saccharina latissima*, *Saccharina japonica*, and *Macrocystis pyrifera* are the fasted growing species according to brown seaweed experts. The farm site selection with favorable environmental conditions is important to cultivate seaweed. The main environmental parameters that condition brown seaweed growth are a combination of cold water, nutrient and light availability, proper salinity, a big sea area, wave activity, and tidal zone differences. There are different techniques to increase productivity and upscale brown seaweed production. Some experts highlighted the importance of seaweed cultivation instead of wild harvesting to increase production volumes and preserve the local marine environment. Selective breeding was repetitively mentioned as a well-known and popular technique to naturally obtain the most productive seaweeds.

3.4 | Technological development and upscaling

Some experts mentioned other emerging technologies to upscale seaweed production, such as offshore seaweed farms, together with already established activities, such as wind farms, seeding lines between windmills, or submersible farms to resist adverse environmental conditions. Technological development would ease seaweed production and the shared infrastructure will make it more economically feasible. Experts mentioned that technological development could entail Western countries achieving similar production volumes to Asia. Limiting factors to upscale include high production costs, the limiting carrying capacity of marine ecosystems, social licensing, sea space limitation, the vulnerability of monoculture, environmental laws constraining seaweed cultivation, and the lack of an established market for the entire value chain in Western countries. Asian suppliers have a long tradition and there are, therefore, different practices for smaller suppliers to learn from them. Breeding techniques, for instance, are highly developed in Asia. In general terms, experts answered that current Asian intensive farming practices cannot be directly applied in Europe. The reasons are mainly environmental protection, social licensing, supply chain transparency, and the differences in harvesting techniques. Asian suppliers use traditional and labor-intensive techniques, which is unfeasible in Europe due to high labor costs making automation necessary.

3.5 | A new market for seaweed-based bioplastics

All brown seaweeds can potentially be used to create alginate-based bioplastic due to their alginate content. When it comes to selecting the most suitable species for this purpose, the key factors are the alginate content and the growth rate of the species. Therefore, *S. latissima* and *S. japonica* were mentioned by experts as the most suitable species to cultivate and harvest as feedstock for bioplastics.

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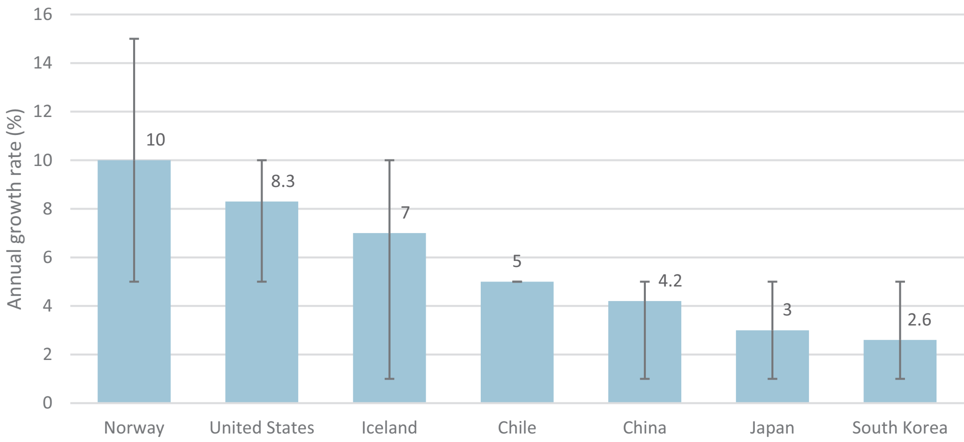

FIGURE 2 Expected annual growth rate (%) in a medium–long term. The values are averaged across respondents. In the error bar: the minimum and maximum values provided by experts. Underlying data for Figure 2 are available in the sheet "Growth rate" of Supporting Information S6.

To know the importance of having the facilities to produce bioplastic close to the seaweed farms, it is important to know the quality of brown seaweed required to create the bioplastic. Even if dry seaweed can be easily transported globally, most experts mentioned various advantages of having seaweed facilities close to seaweed farms. The main advantages are reducing transportation costs and preserving the biomass to maximize the recovery of high-value components from the biomass. These two reasons could make a difference for bioplastics because large volumes and at a competitive price are used to create this biomaterial.

Experts agreed that food is the main target market for brown seaweed, followed by feed, pharmaceuticals, cosmetics, fertilizers, and the alginate market. Other materials, including bioplastics, would be one of the lowest-ranked target markets. The potential of using brown seaweed to produce bioplastics is a matter of how much the market is willing to pay for biomass. Therefore, most of the experts did not see a potential for the current production to shift toward the bioplastic market because it is not as economically profitable as higher-value applications.

There are various potential scenarios for using brown seaweed biomass to produce bioplastic. When the brown seaweed production upscales and the volumes increase, the production prices would gradually decrease. In some decades, depending on investment in research and development to increase the technology readiness level (TRL) of seaweed plastic production, it could be economically feasible to produce bioplastics from brown seaweed. Another potential solution would be using seaweed of lower quality compared to that used for human consumption. This lower-grade seaweed is collected during the second harvest to achieve higher yields and is associated with an increased risk of biofouling that may not meet the standards for human consumption but can still be utilized for bioplastic production.

Combined production methods or sequential extraction were also mentioned by some experts as another opportunity for bioplastics. Other high-value compounds would be used for other purposes and the alginate for bioplastic (Zhang & Thomsen, 2021). In this case, the seaweed would be cultivated to capture carbon and nitrogen and the seaweed is not harvested as frequently as when targeted for use in human consumption. Hence, this seaweed could be used to produce bioplastics.

Some experts foresee the importance of working with bioplastics as a consequence of moving away from fossil fuels. There is a possible scenario for prioritizing bioplastics if the prices for conventional plastics increase or with potential government incentives for companies adopting biopackaging. The extended information on all the interview answers, including relevant quotes, can be found in Supporting Information S3.

3.6 | Identified marginal mix for global brown seaweed suppliers

When the five experts were asked to select the main brown seaweed suppliers in the middle–long term, between 2025 and 2035, all of them selected China, Norway, and South Korea; four Japan; and three Chile, Iceland, and the United States. It is worth mentioning that Australia, Canada, the Faroe Islands, North Korea, and the United Kingdom were selected by at least two experts as main suppliers in the middle–long term. The complete results with the answers can be found in Supporting Information S6.

Figure 2 represents the expected annual growth rate of the marginal suppliers. The graph shows that the largest expected annual growth is from Northern European and North American countries, followed by Chile and then the Asian seaweed producers.

Table 1 displays the expected marginal mix in 2025, 2030, and 2035. The mix shows that an increase in demand for brown seaweed is primarily met by China as the dominant marginal supplier and then by the second group of important suppliers (South Korea, Norway) and in minor share by other emerging suppliers. The result also shows that over time the marginal supplier mix is expected to change with a larger contribution from the emerging suppliers and a decrease in the contribution from the incumbent suppliers.

TABLE 1 Marginal mix of global brown seaweed suppliers in 2025, 2030, and 2035 (ranked from larger to smaller in 2035). Values are averaged across respondents. In parenthesis: the minimum and maximum values provided by experts. Underlying data for Table 1 are available in sheet "Marginal mix" of Supporting Information S6.

Countries	Marginal mix in 2025	Marginal mix in 2030	Marginal mix in 2035
China	73% (40-89)	69% (30-84)	65% (25-80)
South Korea	10% (2-20)	11% (2.5-20)	10% (2-19)
Norway	3% (0.5-5)	6% (2-15)	10% (2-25)
Japan	8% (1-30)	6% (2-20)	5.5% (2-15)
Chile	4.5% (5-10)	5% (5-10)	5% (5-8)
United States	1% (1-3)	2% (1.5-5)	3% (2-8)
Iceland	0.5% (0.5-1)	1% (1-2)	1.5% (1-4)
Total	**100**	**100**	**100**

TABLE 2 Expected market share for bioplastics (ranked from larger to smaller in 2035). Values are averaged across respondents. In parenthesis: the minimum and maximum values provided by experts. Underlying data for Table 2 are available in the sheet "Bio-based plastic" of Supporting Information S6.

Countries	2025	2030	2035
Chile	1% (1-1)	5% (5-5)	10% (5-20)
Iceland	1% (1-1)	3.7% (1-5)	8.7% (1-20)
United States	1% (1-1)	3.7% (1-5)	8.7% (1-20)
Norway	2.6% (1-5)	5.2% (1-10)	8.2% (1-20)
South Korea	1% (1-1)	4.2% (1-5)	8.2% (1-20)
China	1.8% (1-5)	3.4% (1-5)	5.2% (1-10)
Japan	1% (1-1)	3% (1-5)	4.3% (1-10)

The results on the market share for bioplastics are listed in Table 2, which shows the total production of brown seaweed expected to be allocated to bioplastics. There is no substantial difference in the share of bioplastics between the suppliers. The production is expected to grow significantly in the long term and, according to these numbers, with an upscaled production in 2035, the market share for bioplastics will be larger than in the middle term.

3.7 | Validation of results

The responses to the validation questionnaire indicated that most of the experts considered the identified marginal suppliers as a fair match to their expectations. Specifically, most participants indicated a "fair match," one participant indicated a "good match," with only one participant rated the match as "excellent." No participants rated the match as "poor" or "very poor."

The most uncertain variable identified by the experts was the percentage of shares, with some experts pointing to uncertainties in identifying marginal suppliers as the main reason. Some experts noted that Norway had a bigger share than expected, while others expected other European countries to appear in the list of marginal suppliers. Additionally, there was a general opinion that Asian suppliers would have a slightly bigger share in the future than the one anticipated in the results. In general, the predictions about growth rates were viewed as uncertain. The insights from the validation step indicate that while there is a general agreement among experts that the identified marginal mixes are valid to a fair to good extent, there is not a full agreement among experts regarding the specific shares of each supplier and the assessment is characterized by uncertainties. This result was to some extent expectable as the shares are obtained averaging the estimates of different experts and predictions about the future are intrinsically uncertain and, therefore, all results are here provided with ranges.

4 | DISCUSSION

In general, we observe a good alignment between interviews, both questionnaires and literature information, and this suggests that the proposed method provides results that are sufficiently robust for the case of brown seaweed. The expert elicitation questionnaire results (Step 4) indicate that Northern European and North American countries are expected to grow in the next years. That aligns with the experts' insights: these countries are

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still in the early stage of brown seaweed cultivation but have the necessary tools to upscale the production. The literature and the interviewed experts agree that Norway has the technology, infrastructure, knowledge, and optimal environmental conditions to increase production (Broch et al., 2019; Handå et al., 2013; Stévant et al., 2017; van den Burg et al., 2021). Chile is also expected to keep growing in the future. Currently, it is one of the main brown seaweed producers and its production is mainly based on wild harvest. In the interviews and the literature, we see that a transition toward aquaculture is necessary to upscale Chilean production (Buschmann et al., 2008). The Asian countries are expected to have a smaller growth rate than the European and American countries. Based on the interviews and the literature (Hurtado et al., 2019; Kim et al., 2017; Zhang, 2018), this can be explained because the Asian countries have an established market, intensive production, many exploited areas, and a high internal brown seaweed demand (Hu et al., 2021; Hwang et al., 2019). China is foreseen to be the main supplier, but the rest of the countries are expected to increase their future share in the marginal mix.

The marginal mix results can be used in consequential LCA studies for brown seaweed-based products, such as bioplastic. The marginal mix is intended to develop country-specific inventories of seaweed farming technologies, for the listed countries in the mix and combine them based on the proportions provided in this study. For instance, for a reference flow of 1 kg of seaweed demanded globally, 0.73 kg of seaweed is produced in China (cf. Table 1).

Although some limitations to the methodology can be discussed, the results of this study were validated in several means. It can be argued if 11 interviewees are enough to obtain valid results and how it affects the quality of the results. The selected experts for the interviews and both questionnaires were highly qualified and diverse in their backgrounds, providing a solid foundation for valid information. The focus was on selecting the right experts over receiving many respondents. After a few interviews, a satisfactory level of data saturation was reached. Moreover, the results from the interviews were triangulated with the answers from both questionnaires, validating the questionnaires' answers likewise. Therefore, by selecting different seaweed experts, the results would be very similar and reproducible to a good extent. Regarding the analysis of interview data, the answers to the questions were summarized systematically (cf. Supporting Information S3) and it is likely that practitioners analyze the interviews to derive the same results. Another limitation comes with the questionnaire on Step 4, as experts found it challenging to make accurate predictions given the uncertainty about the future. Experts were instructed to state their expectations based on their current level of knowledge on the topic and we acknowledge the limitations of an expert-based assessment. The validation questionnaire (Step 5) helped to ensure the reliability and accuracy of the findings. The idea behind this research is that market trends are also based on guesses and, in the case of brown seaweed, there are other factors to consider that are not reflected in the market analysis.

This method is intended to be used in the assessment of emerging technologies and conditions of data scarcity and high uncertainty. The proposed mixed qualitative/quantitative methods approach might not apply to established technologies and where larger amounts of quantitative data are available. In those cases, quantitative methods might be more appropriate (Buyle et al., 2018; Ghose et al., 2017; Sacchi, 2018; Schmidt & Weidema, 2008). However, this expert prediction-based method is appropriate for identifying and understanding marginal brown seaweed suppliers.

5 | CONCLUSION

In this research, we investigated how QST can be applied to identify marginal suppliers in the case of brown seaweed. The main theoretical highlights from the study are that current methods to identify marginal suppliers do not properly address the complexity of emerging technologies where uncertainty is substantial, data are scarce and there is a need to rely on and combine systematically both qualitative and quantitative information. For these reasons, existing methods do not apply well to the case of brown seaweed production intended as an emerging technology. We conclude, in this study, that the steps in the method of QST, proposed by Cabello et al. (2021), can be applied successfully to identify marginal suppliers in cases of scarce quantitative data or when qualitative information is essential to consider.

In terms of novelty for seaweed and LCA research, this research goes beyond previous studies. On the one hand, it gathers data on brown seaweed supply, such as the global production, market, natural constraints, production, technology to upscale the production and provides novel information on using brown seaweed to produce bioplastics. Finally, novel information on brown seaweed marginal mix is provided which can be used to identify marginal suppliers in consequential LCA studies.

The results show that China is the main marginal supplier and is expected to be the marginal supplier in the middle–long term. We also see that seaweed aquaculture is key to upscale brown seaweed production because it enables obtaining larger biomass volumes. The brown seaweed suppliers in Northern Atlantic, still in an early development stage, are forecasted to increase significantly in the middle–long term. According to our results, a large market share for brown seaweed bioplastic is not feasible in the short term given that the price of the seaweed for this purpose is lower than for other applications. There are different options to increase the market share of bioplastics in the current market. Findings suggest that the use of brown seaweed to produce bioplastics could be a co-product of pricier target markets. We identify different alternative scenarios to materialize this outcome: using the parts of the seaweed not destined for food, using the lower quality seaweed that is not suitable for consumption, or a multi-functional biorefinery model where the alginate is used to produce this bioplastic, and the remaining components for other purposes.

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With the expected global growth in brown seaweed production, the market share for bioplastics is expected to be higher in the long term. We conclude by recommending these scenarios and production factors to be considered in future LCA studies of seaweed-based products.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the Supporting Information of this article.

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SUPPORTING INFORMATION

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