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Seaweed kombucha: Exploring innovation in marine resources in Iceland

Martyn Jones [a,b], Catherine Chambers [a,c,*], Peter Krost [a,d]

[a] University Centre of the Westfjords, Ísafjörður, Iceland
[b] Marine and Freshwater Research Institute, Ísafjörður, Iceland
[c] Stefansson Arctic Institute - University of Akureyri, Akureyri, Iceland
[d] CRM, Coastal Research & Management, Kiel, Germany

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ABSTRACT

The productive marine waters around Iceland have led to the development of an economically important fisheries industry and strong cultural connections to seafood, yet seaweed remains an underutilized resource in domestic food products. This research was designed as an innovation/feasibility exploration using the case study of the development of a local seaweed-flavoured kombucha in the Westfjords of Iceland, with the research aims to: 1) develop an Icelandic seaweed kombucha, and 2) explore consumer preferences. Different recipes of kombucha infused with seaweed were created, and a consumer taste test was performed with a small group of consumers (n = 54). An important part of the study was also the analysis of potentially harmful compounds in the seaweed, of which heavy metals and iodine analyses were carried out on locally sourced dulse (*Palmaria palmata)* and sugar kelp (*Saccharina latissima)*. The results were compared with EU regulations and Icelandic regulations. Results show varying elevated levels of heavy metals and iodine in both species, but heavy metal guidelines for seaweed products are unclear in the Icelandic regulatory scheme. Taste test results suggest that potential kombucha customers lie in the younger generations, and there were variations by nationality, for example 25% of Icelandic respondents had tried kombucha prior to the taste test. Given the increasing trends of health food in general, an expansion of seaweed food products, and Iceland's focus on the blue economy, this research confirms that while focus should still be placed on updating toxin limit regulations and research, there is a potential for future Icelandic seaweed kombucha products.

1. Introduction

1.1. Seaweed food products

There have been multiple applications of seaweed globally throughout time. It was used in the past as a source of food and fertilizer, and its use in modern times has diversified into markets for seaweed-extract products such as cosmetics and biofuels (McHugh, 2003). Seaweed food products are also expanding, and this increase in interest is due to a consumer focus on novel and wholesome products (Garland, 2020; Mac Monagail et al., 2017; Mouritsen et al., 2013). Around the world, the number of different algal species is in the thousands, yet the focus for human consumption is limited to relatively few species (Borowitzka, 1998), and seaweeds on their own play a relatively small role in the day-to-day diet in most cultures (Mouritsen, 2017). Culinary uses include seaweed as an outer layer in sushi, an alternative to salt, an additive to soups and salads, as well as a side to fish dishes (Ikeda, 2002; Tarver, 2015; Yamaguchi and Ninomiya, 2000). Most of the seaweed extracts are the hydrocolloids (*e.g.* alginate, carrageenan and agar) which are used as thickening agents, colour enhancers or moisture retaining agents and are found in a large array of everyday food items such as ketchup, mayonnaise, ice cream and soup (Jaspars and Folmer, 2013).

Overall, seaweeds offer many benefits for human health that range from helping to promote a healthy heart and gut, helping to fend off cancer and stomach ulcers or aiding to keep sugar levels under control (Jaspars and Folmer, 2013). In fact, it is even believed that seaweeds were vital for humans in the evolution of the modern brain (Cornish et al., 2017). Seaweeds are known to have multiple antioxidants, which are a response to the natural conditions that intertidal seaweeds have to endure such as prolonged periods under the sun (Jaspars and Folmer, 2013; MacArtain et al., 2007). Seaweeds contain notable levels of minerals, vitamins and proteins, often higher concentrations than in land-based foods (MacArtain et al., 2007; McHugh, 2003; Mouritsen

* Corresponding author. Borgir við Norðurslóð, 600 Akureyri, Iceland.
E-mail address: catherine@unak.is (C. Chambers).

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et al., 2013; Rajapakse and Kim, 2011). For the most part, eating seaweed is not problematic nor unsafe, although high consumption can be risky in terms of exposure to heavy metals and iodine (Bailey et al., 1999; Brownlee et al., 2011; Rajapakse and Kim, 2011; MacArtain et al., 2007; Roleda et al., 2019). Heavy metals like arsenic can come from different human sources such as burning fuels or industrial level processes, but also from naturally occurring levels in rock (ANSES, 2020).

With nearly all species of seaweed being safe for consumption (Mouritsen, 2013a) there is a vast variety of seaweed available that can be introduced to culinary dishes, and its potential to contribute to the taste and texture of foods has not been fully capitalized (Mouritsen, 2017). Consumer awareness of health benefits may be low (Kadam and Prabhasankar, 2010), and on top of this, simply referring to macroalgae as 'seaweed' may carry a negative connotation. In fact, there are calls to highlight seaweeds as 'sea vegetables' - an enjoyable food source, rather than 'weeds' (Goodyear, 2015; Jaspars and Folmer, 2013; Mouritsen, 2017). At the same time, the seaweed trend points to a relatively recent increase in its use in food and drink products within Europe, showing 147% more novel products in the year 2015 utilized seaweed flavours compared to 2011 (Mintel, 2016) and the trends of worldwide increased seaweed production and product development is expected to continue (Rogel-Castillo et al., 2023).

1.2. Towards an Icelandic seaweed kombucha

In Iceland, there exists a strong relationship to the sea that is part of the nation's heritage (Smith and Chambers, 2015), in part due to the commercial fisheries industry. Although the number has decreased over time, the Icelandic nation still consumes 315 g of seafood per capita on a weekly basis (Gunnarsdóttir et al., 2022). Seaweed has long existed as a food item in Iceland, but this is limited mostly to one species, dulse (*Palmaria palmata*), found widely the northern Atlantic Ocean in mid-shore habitats (McHugh, 2003; Mouritsen et al., 2013), as kelps are not a popular feature in the diets across the nation (Gunnarsdottir et al., 2009). Historically, sun-dried dulse served as an item used for trade (Mouritsen et al., 2013) but was also consumed domestically with stews or butter and even in difficult times when other food was in short supply (Hallsson, 1964). Dulse can be a valuable source of protein, depending on the harvesting season (Galland-Irmouli et al., 1999). Today dulse is still eaten in Iceland with a resurgence of interest from younger generations due to its functional properties such as a source of omega-3 polyunsaturated fatty acids, iodine and potassium (Svanberg and Ægisson, 2012); in fact, the high consumption rate of dulse is thought to contribute to low levels of thyroid health issues in Icelanders (Veal, 1997) along with the general high levels of fish consumption (Gunnarsdottir et al., 2009).

The goal of the project described in this paper was to explore the feasibility of production and market potential of a new seaweed-based food item in a local and domestic Icelandic market. Kombucha was chosen because of its relatively low presence in Iceland, at the time of research there was only one company producing kombucha in Iceland, and there were no seaweed kombuchas available in Iceland. Kombucha is an effervescent cold tea produced by fermentation from a symbiotic culture of bacteria and yeast (SCOBY) with a mix of sugar and tea (Aung and Eun, 2021; Coelho et al., 2020; Dufresne and Farnworth, 2000; Francisco et al., 2021; Villarreal-Soto et al., 2018). Kombucha is thought to originate in China but has become known in the Western world due to health benefits such as antioxidative effects and treatment of elevated levels of cholesterol (Aung & Eun, 2021; Coelho et al., 2020). There has been continued market growth for kombucha due in part to its recognition as an alternative soft drink (Kim and Adhikari, 2020; Tahmassebi and BaniHani, 2020; Vartanian et al., 2007). In 2018, kombucha had an estimated $1.5 billion USD market value (Kim and Adhikari, 2020).

In a larger context, the project was also situated in the current discourse around the growth of seaweed in Iceland's blue economy (Björnsson et al., 2023) and the potential for seaweed industries and products to contribute to development in rural communities. The seaweed kombucha development was deliberately carried out in Ísafjörður, the administrative capital of the Westfjords. The Westfjords region, population 7000, holds one-third of the entire coastline of Iceland and a rich history of maritime industries, and therefore makes an interesting region to test the development of new maritime industries and products. A report from a working group commissioned by the Icelandic Ministry for Food, Agriculture and Fisheries promotes utilising seaweed in a variety of ways (Björnsson et al., 2023) and seaweed ventures in the Westfjords currently exist with rockweed harvesting (Lee, 2018). At the same time there is still room for innovation regarding macroalgal products and further marine resource diversification (Garland, 2020).

The aim of the research was twofold: 1) to develop an Icelandic seaweed kombucha, and 2) to explore consumer preferences through a taste test. This feasibility study takes a proof-of-concept approach to create a holistic understanding of the major aspects that should be considered for a seaweed kombucha company in a rural community (See (Jones, 2021) for more details). We explored these ideas from several angles, essentially putting ourselves in the innovation mindset of a blue economy entrepreneur. Therefore, later phases of formal product development, market testing, business plans, sensory groups, or marketing plans were not part of this project. At the same time, it was important to document the process and explore potential consumer reactions, especially because for novel food products, there is a need to understand and outline what consumers think about these products (Santeramo et al., 2018). Therefore, a modified taste test method was developed as a practical aid to explore, understand and highlight any hurdles in relation to creating safe seaweed food and drink products, and second, to test local opinions on potential seaweed products (based on sensory evaluation methods in Gengler, 2009, but with modifications). Two seaweeds were chosen as the focus of this project: dulse, due to the cultural connections and history as discussed previously, and sugar kelp (*Saccharina latissima*). Sugar kelp is widely found in coastal areas north of the equator (Monteiro et al., 2021), easily accessible in Iceland, and contains high levels of the natural sweetener mannitol (Mouritsen et al., 2012).

2. Methods

2.1. Kombucha production process

Dulse and sugar kelp for the kombucha were sourced from coastal sites around the northerly Westfjords (Fig. 1). The sites (Ósvör, Arnarnes, Strandsel and Þingeyri) were chosen for their ease of access and samples were gathered during low tide using scissors in September

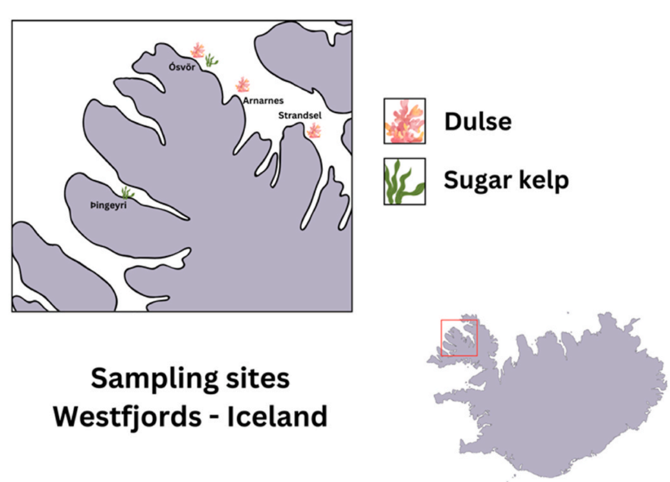

Fig. 1. Seaweed sample sites in the Westfjords (Google, n.d.).

2020 and February 2021. Plastic 4L bags were filled with the fresh collected seaweeds from within a 5 m transect at the site. For the dulse, no more than one-third of each plant was harvested and the holdfasts were left intact (see published guidance on seaweed harvesting - Natural Resources Wales, 2018). For the sugar kelp, the fronds were cut above the growth point with the holdfasts also left intact (Natural Resources Wales, 2018). No free-floating or drift seaweeds were gathered or used, as drift seaweed can have lower levels of nutrition and minerals and be more susceptible to developing mold (McHugh, 2003). Further washing took place inside in the kitchen facilities at the Djúpið Innovation Shelter in Bolungarvík where both seaweed species were washed in fresh cold water at least twice, any intact organisms that were not found and removed on site were removed during washing, along with any degraded fronds. The seaweed was dried in bulk in a kitchen oven at 50 °C, with the oven door left ajar, for between six to nine hours until crisp and flaky.

The preparation of kombucha took place in two fermentation stages (Fig. 2). The first included creating a heated tea and sugar infusion which was then brought down in temperature. This was followed by adding previously fermented kombucha that makes up to around one-tenth of the infusion along with the SCOBY (Fig. 3) (Coelho et al., 2020). The kombucha infusion was then covered with a cloth (Greenwalt et al., 2000), for the purpose of preventing entry to any contaminants (Coelho et al., 2020). The kombucha was left to ferment for around 1 week at room temperature (Greenwalt et al., 2000). The secondary fermentation process involved removing the SCOBY and mixing the kombucha liquid with a flavour infusion. This process further fermented and produced gases. Some of the liquid and the SCOBY from the first step was saved and used to produce more kombucha (Coelho et al., 2020).

Recipes and flavour infusions were tried and tested internally with volunteers throughout the process from June 2020 until April 2021.

Fig. 3. SCOBY (symbiotic culture of bacteria and yeast) pellicles sitting in kombucha liquid from an initial trial batch before flavouring or infusion experiments began.

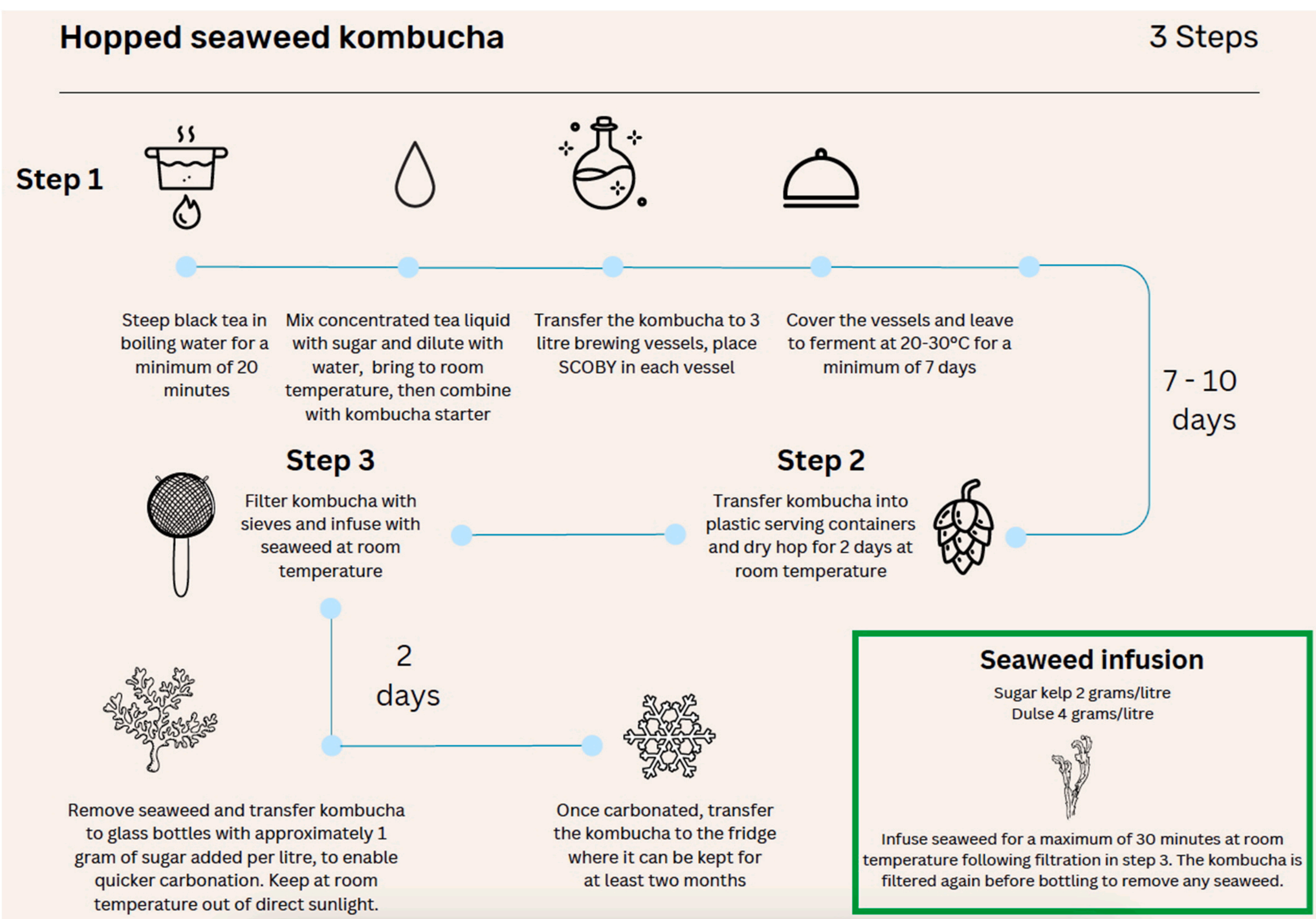

Fig. 2. Kombucha brewing process. The inset in the green box explains the seaweed infusion process, which takes place after Step 3.

Infusions included banana, apple, orange, rhubarb, chilli ginger, chilli jalapeno, crowberry, mixed berry, strawberry, turmeric, raspberry, hibiscus, lavender, camomile and hops. After trying the various flavours, the hop infusion was chosen for the taste test (see section 2.3 below) and was then infused with both seaweed species (See Fig. 2 for seaweed infusion details).

2.2. Heavy metal testing

Because of the possibility of heavy metal contamination of seaweeds, it was important to carry out testing in the early phases of this project. The focus in this study was upon iodine, cadmium and arsenic, based on previous studies that highlighted these elements as particularly high-risk elements in macroalgae (Banach et al., 2020). Additional testing to explore the nutritional and antioxidant content was not addressed in this study due to budgetary restraints and the multi-method nature of the project. The sampling was completed in two sets. Sample set one consisted of dulse from Ósvör, Arnanes, and Strandsel, as well as sugar kelp from Ósvör and þingeyri (Fig. 1), collected from September 2020–February 2021. Following the harvesting and drying methods described in section 2.1, dried samples were subsequently stored in tightly closed plastic bags in a cool, dry area, out of direct sunlight, until they were sent for testing to TosLab in Tromsø, Norway (https://toslab.no/) for analysis of iodine, arsenic and cadmium.

Sample set two consisted of samples of the final kombucha products. To create the seaweed kombucha samples, blanching was used for the sugar kelp to reduce iodine levels. The sugar kelp was blanched in freshly heated water for 120 s before being placed into cold water for a minimum of 60 s. This was done because the study by Nielsen et al. (2020) found that iodine was reduced the most in sugar kelp when placed in water that was heated to 80 °C for 2 min. The sugar kelp alone was not tested for iodine after blanching, only the kombucha sample infused with sugar kelp was tested. Blanching was not used for the dulse due to lower iodine levels from the wild-collected samples (Table 1). Unflavoured kombucha was infused with either species of seaweed separately at room temperature (see Fig. 2 for infusion details). The infused kombucha samples were sent to Toslab in 330 mL plastic bottles, to be analysed for lead, mercury, cadmium, total arsenic and iodine.

The analysis was carried out as per the determination of halogens in food and dietary supplement (SS -EN ISO 17294–2:2016, US EPA Method 200.8:1994). Prior to analysis the sample was digested according to B-PF51-ALK as per the Certificate of Analysis (CoA) provided by ToSlab (https://toslab.no/). As per the CoA, no measurement of uncertainty was used because uncertainty is reported only for detected substances with levels above the reporting limits. One measurement was taken for each seaweed-infused kombucha sample, kombucha without seaweed was not tested due to budgetary limits. For sample set 1, the moisture content of samples was estimated using higher and lower levels where Badmus et al. (2019) highlight that as little as approximately 15% of the seaweed can be dry matter and the remaining content being moisture and Mouritsen (2013b) highlights lower variations from 10% dry matter up to higher levels of 30%, with the rest of the seaweed being made up of water. Thus, a high estimate of 85% and a low estimate of 70% moisture are used. Water content was estimated because water content was not measured initially since the initial research plan was to follow French recommended limits that are based upon the dry weight of the seaweed (See Table 1). In order to calculate estimations of wet weight content for the seaweed samples, the following calculation was used:

$$wet\ weight = dry\ weight * \frac{dry\ mass\ of sample\dagger}{100}$$

†The Dry mass of a sample is calculated as (100 - moisture content).

Table 1
EU recommendations on heavy metals and iodine in seaweed. French recommendations are included for comparison.

Heavy metal & iodine	EU limit	French recommended limits
Arsenic (total)	No limit included that relate to seaweed (a)	N/A
Arsenic (inorganic)	No limit included that relate to seaweed (a)	3.0 mg/kg dw (dry weight) (c)
Cadmium	3.0 mg/kg ww (wet weight) (a)	0.5 mg/kg dw (d)
Iodine	No limit included that relate to seaweed (a)	2000 mg/kg dw (c) (d)
Lead	3.0 mg/kg ww (a)	5.0 mg/kg dw (d)
Mercury	0.1 mg/kg ww (a) 0.01 mg/kg - not specified if dry weight or wet weight (b)	0.1 mg/kg dw (d)

(a) (European Union, 2006).
(b) (European commission, 2018b).
(c) (AFSSA, 2009).
(d) (ANSES, 2020).

2.3. Taste testing

The taste test was developed as a practical aid to explore, understand and highlight any hurdles in relation to creating safe seaweed food and drink products, and second of all to give indications of local opinions on potential seaweed products in a general questionnaire format. Therefore, the taste test was based loosely on sensory evaluation survey methodology (Gengler, 2009) but modified to include questions on general consumption habits and opinions as are present in basic attitudinal surveys on food (Pétursdóttir, 2017). The first taste testing event was held at a local café, Heimabyggð. A public event ad was created online on social media to advertise the date, time and location of the event. The online ad was shareable amongst the public to encourage and promote attendance and awareness, the targeted sample population for the event was the general public over 18 years of age, with no specific target population between locals and non-locals or in terms of nationality, gender or age (aside for being 18 and over). A sign was set up outside the café on the day to attract more potential participants (Fig. 4). The café chosen was in a central location where it was assumed foot traffic would be higher and therefore increase the chances of potential participants. Voluntary response sampling (McCombes, 2019) was employed, which allowed for sampling random customers at the café, particularly those who had not seen or responded to the online advertisement. This method depends upon participants opting to take part, rather than the researcher looking for and selecting participants to partake in a survey (McCombes, 2019). Due to Covid restrictions at the

Fig. 4. Advertisement used for the taste test outside the Heimabyggð café.

time, participation had to be capped at 44 since the researchers and café staff counted towards the total gathering limit of 50 individuals.

In total, the maximum 44 individuals took part in the café taste testing. Prior to taking part, participants read information concerning the project, and gave their consent to participate. The taste test survey was written in English and Icelandic and consisted of two sections, the survey was printed with the kombucha taste test questions on the back side and general consumption trends and opinions on the front side. Participants were requested to fill out the form individually and to start with the front page before tasting the kombucha, which was designed to gather marketing information on participants' awareness of kombucha, monthly spending on non-alcoholic fizzy drinks, and preferences towards fizzy drinks in comparison to health drinks and kombucha.

Participants were then given three samples in a semi-blind test, with the participants unaware of which sample was which, two assistants were present during the event to help with restocking kombucha, pouring samples and explaining the survey to participants. Participants were provided with a 200 mL capacity biodegradable cup that was filled no more than halfway for each sample. Participants were given 'sample A' which was sugar kelp hopped kombucha, followed by 'sample B' which was hopped kombucha and finally 'sample C' which was dulse hopped kombucha. In the second section, participants included their preference for each kombucha, along with questions on purchasing potential and willingness to pay for the product. At the end of the taste test the different sample flavours were revealed to the participants. Students and staff of the local university participated in a similar event three days later, with ten additional people partaking in the taste test, resulting in a total of 54 responses for both taste testing events. This session was not advertised in advance, participants were asked if they would like to partake and the process followed the same steps as the prior taste test. Results were analysed statistically using non-parametric tests (R Core Team, 2021) on independent variables (nationality, age, gender and education), and dependent variables (composed of all the survey questions such as purchasing of kombucha, likelihood to look for healthier choices in fizzy drinks, etc.) The Kruskal-Wallis test was used to ascertain any differences between the age, nationality and education of participants against any significant results in relation to having tried kombucha, having heard of kombucha, the likelihood to buy kombucha, the likelihood to recommend kombucha, the preference for each individual kombucha, etc. For all tests significance was assumed where $p < 0.05$.

3. Results

3.1. Kombucha taste test results

In terms of general participant demographics, there were slightly more females ($n = 30$) than males ($n = 23$), age ranged from 22 to 62 years, 95% had a university education, and there were 16 different nationalities but all were currently living in Iceland, with the biggest groups being Icelandic ($n = 16$) and German ($n = 14$). Although statistics were performed to test the variations in demographic data with the taste test perceptions and general survey responses, statistically significant results were only found for the consumption of fizzy drinks on a weekly basis, where those in the age group 18–24 were more likely to consume fizzy drinks weekly compared to those in the age group 55–64 ($p < 0.05$). The statistical tests were carried out to verify if any of the reported trends (*e.g.* "kombucha preferences") were significant in relation to the demographic data, such as age, gender etc. However, no other statistically significant results were found for the results presented and therefore general trends were also explored and reported here.

A majority (76%) of those surveyed had heard of kombucha, and of those who had not heard of kombucha before, they tended to be above 35 years old, male and Icelandic. Similarly, 69% of participants had tried kombucha before, however, only 25% of the Icelandic participants had tried kombucha. From the 69% of participants (37 people) that had tried kombucha, 38% (14 people) also purchased kombucha monthly. Although it is perhaps not surprising, it is important to note that 85% of respondents agreed or strongly agreed on a Likert scale of 1 (strongly disagree) to 5 (strongly agree) to the statement "I believe seaweed is a product that is currently underutilized."

On the taste test, none of the participants had a strong dislike for any of the kombucha samples (Fig. 5). By grouping the responses for 'like very much' and 'like' together, the results are fairly similar for all three samples, with the highest preference for the dulse hopped blend (54%). Overall the results show slightly higher preferences for the seaweed blends, although there were several participants who abstained from providing a response for each sample (Fig. 5). However, the results from the statement "I find there is a lot of different between the three samples" were split. The percentage who agreed or strongly agreed that there was a lot of difference (42%) was not significantly higher than the number of participants who disagreed or strongly disagreed (35%) (Fig. 6). Finally, there was no statistical difference between the willingness to pay, asked as an open-ended question in reference to a 330 mL bottle of each kombucha product. The average price participants would be willing to pay for each kombucha sample during the taste test was 1496 ISK/L - ranging from 1373 ISK/L for the sugar kelp hopped to 1561 ISK/L for the hopped with no seaweed infusion.

3.2. Heavy metal and iodine analysis

For dulse collected in local samples, using 85% average moisture content, the concentration of all heavy metals in all samples fell below the EU food supplement levels for seaweed (Table 1, Table 2). When using 70% moisture content, the heavy metal contents were also lower than EU limits related to food supplements containing seaweed for the dulse samples (Table 2). In terms of iodine content in dulse, it was under French limits for all samples. Cadmium was over French limits (Table 1) in all dulse samples but below EU limits (Table 2). For the sugar kelp, both samples were below EU limits for cadmium when using 85% and 70% moisture contents. However, cadmium levels in the sugar kelp exceed French recommended limits (Table 2). Arsenic is elevated in both sugar kelp samples, to the point where speciation analysis would be needed to verify inorganic arsenic concentration. As for sampling site Ósvör, iodine limits for sugar kelp were below French recommended limits whilst samples from þingeyri exceeded the limit (Table 2).

Heavy metal levels in the finished seaweed kombucha product fall below EU and French limits and recommendations where applicable (Table 3). Iodine falls within French limits for both kombucha samples. The arsenic and iodine content falls below EFSA tolerable intake and benchmark dose levels for both samples (Table 3). There are no limits for soft drinks or kombucha specifically in relation to iodine and heavy metals in EU regulations (European Union, 2006). The tolerable intakes by EFSA were included in the study as a reference for safe consumption regarding the kombucha.

The kombucha analysis shows that both dulse and sugar kelp kombucha samples are below the benchmark dose levels and tolerable intakes. For the dulse kombucha which had higher levels of heavy metals and iodine than the sugar kelp, 2.43 L of dulse kombucha would need to be consumed to be within the benchmark dose level for arsenic, 49 L would exceed the cadmium tolerable weekly intake (TWI), 526.5 L would exceed the mercury TWI if all mercury content was methylmercury, or 1620 L for inorganic mercury TWI if all mercury content was the inorganic form, lastly 71 L would fall within the BMDL10 (Benchmark Dose Lower Bound) for lead; this calculation uses an Icelandic average body weight of 81 kg from the study by Matthiasdottir et al. (2010). This information highlights that the kombucha blends are safe for consumption, particularly since a serving would normally range from 330 to 500 mL.

MAST (Icelandic Food and Veterinary Authority) follows EU regulations on heavy metals, and for arsenic and iodine they refer to The European Food Safety Authority's (EFSA) tolerable intakes (Jónsdóttir,

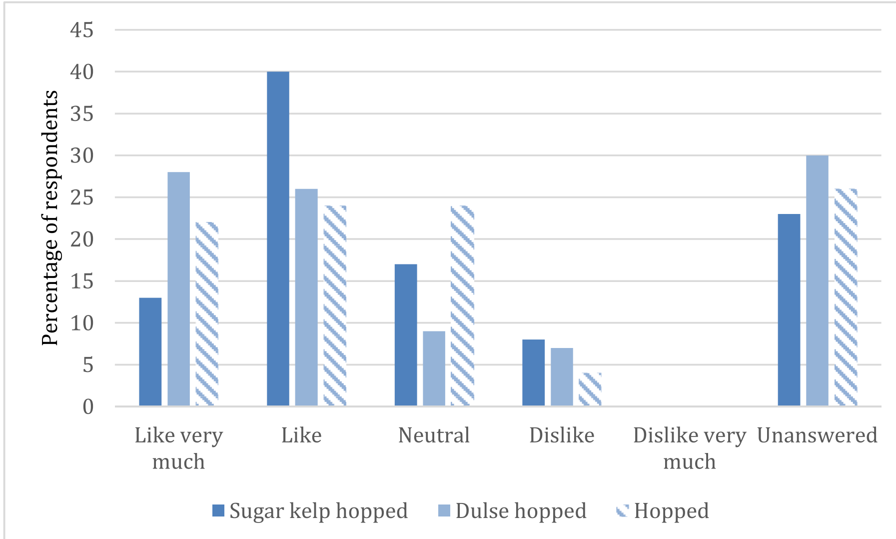

Fig. 5. Percentage breakdown of the taste test participant's preference for each kombucha sample in the taste test for the question "Sample A/B/C: (circle one) Disklike very much/Dislike/Neutral/Like/Like very much." Results are transposed here to show "like very much" first. (sugar kelp hopped n = 41 answered, 13 unanswered; Dulse hopped n = 38 answered, 16 unanswered; hopped = 40 answered, 14 unanswered).

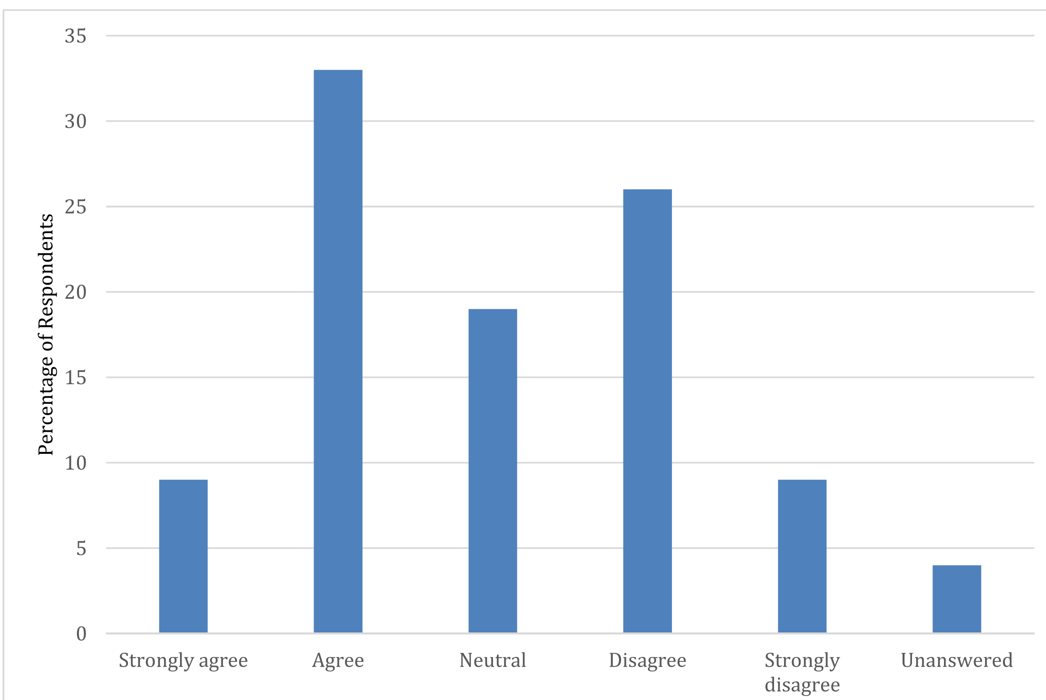

Fig. 6. Percentage breakdown of taste test participants' responses to agreement to the statement "I find there is a lot of difference between the three samples" on a scale of 1(strongly disagree)-5(strongly agree). Results are transposed here for easier reading. (n = 52 answered, 2 unanswered).

Table 2
Wild-harvest seaweed heavy metal analysis results from sample set 1 (Wild collected seaweed from 5 locations, which was dried and sent for heavy metal analysis). As = Arsenic; Cd = Cadmium; I = Iodine; Pb = Lead; Hg = Mercury.

Seaweed	Location	Collection date	As content[a]	Cd content[a]	I content[a]	Pb content[a]	Hg content[a]
Dulse	**Arnarnes**	September 2020	2.47 (±0.50)	1.36 (±0.18)	150	Not tested	Not tested
	Ósvör	September 2020	6.12 (±1.22)	2.02 (±0.27)	161	Not tested	Not tested
	Strandsel	February 2021	8.62	3.02	430	<0.03	<0.02
Sugar kelp	**Ósvör**	September 2020	65.1 (±13.0)	1.58 (±0.21)	801	Not tested	Not tested
	Þingeyri	September 2020	67.7 (±13.5)	2.51 (±0.33)	2900	Not tested	Not tested

[a] *All results are mg/kg dry weight (dw). Measurement of uncertainty in brackets which is reported only for detected substances with levels above the reporting limits as* per the *certificate of analysis.*

Table 3
Seaweed kombucha heavy metal analysis. As = Arsenic; Cd = Cadmium; I = Iodine; Pb = Lead; Hg = Mercury.

Kombucha type	Inorganic As content	As content	Cd content	I content	Pb content	Hg content
Dulse	<0.01 mg/kg	62.4 (±11.4)	4.12 (±0.41)	<0.2 mg/kg	0.722 (±0.106)	0.2
Sugar kelp	N/A	3.64 (±0.69)	0.456 (±0.052)	<0.2 mg/kg	<0.5	<0.2

*All results are µg/kg unless otherwise indicated. Measurement of uncertainty in brackets which is reported only for detected substances with levels above the reporting limits as per the certificate of analysis.

I., personal communication, February 5, 2021) (Table 1). The limits which are set by EU regulations do not refer specifically to seaweed itself but rather refer to supplements that are destined for consumption and are made for the most part out of seaweed in dry form (European Union, 2006). EFSA and the formerly Scientific Committee on Food (SCF) has given scientific opinions on arsenic and iodine (Table 4) in relation to intake ((CONTAM - EFSA Panel on Contaminants in the Food Chain, 2009); Scientific Committee on Food of European Commission, 2002). A personal communication with MAST clarified that these are neither recommendations nor regulations but an opinion that the EU can choose to integrate (Ólafsson, G., personal communication, May 20, 2021). EFSA has not set a weekly or daily limit for inorganic arsenic (CONTAM - EFSA Panel on Contaminants in the Food Chain, 2009) but rather a benchmark dose level is proposed (see Table 4), from 0.3 to 8 µg/kg of body weight which is applicable on a daily basis. Inorganic arsenic within this range can lead to a higher risk of certain illnesses and disease (CONTAM - EFSA Panel on Contaminants in the Food Chain, 2009).

Table 4
EFSA tolerable intakes on arsenic, iodine, cadmium, mercury & lead.

Heavy metal or Iodine	Tolerable intake (daily/weekly)	Notes
Inorganic arsenic (a)	No tolerable daily or weekly intake is set by EFSA. Previous weekly limit set by JECFA of 15 µg/kg of body weight has been deemed by EFSA as no longer suitable (a) (c)	EFSA have set a daily benchmark dose level (BMDL01) for inorganic arsenic. This is set at 0.3µg–8µg/kg of body weight.
Iodine - Adult limits (b)	600 µg/day. (b)	This is the upper limit for iodine and also applies to women going through pregnancy, and those going through periods of lactation.
Iodine - Child limits according to specific age brackets (b)	The following upper value are µg/day: 200 for children aged 1-3 250 for children aged 4-6 300 for children aged 7-10 450 for children aged 11-14 500 for children aged 15–17 (b)	These are upper limits for the corresponding age groups.
Cadmium (d)	2.5 µg/kg of bodyweight (d)	Refers to weekly intake (d)
Methylmercury (e)	1.3 µg/kg of bodyweight (e)	Refers to weekly intake (e)
Inorganic mercury (e)	4 µg/kg of bodyweight (e)	Refers to weekly intake (e)
Lead - Adult limits (f)	No EFSA daily or weekly tolerable intake (f)	EFSA have set (BMDL01) 1.50 µg as well as (BMDL10) 0.63 µg/kg of bodyweight. Both refer to daily intake (f).
Lead - Child limits (f)	No EFSA daily or weekly tolerable intake (f)	EFSA have set (BMDL01) for children which is 0.50 µg/kg of bodyweight. This refers to daily intake (f).

(a) (CONTAM - EFSA Panel on Contaminants in the Food Chain, 2009).
(b) (Scientific Committee on Food of European Commission, 2002).
(c) (Joint FAO/WHO Expert committee on Food Additives, 1989).
(d) (European Food Safety Authority, 2012a).
(e) CONTAM, 2012.
(f) (European Food Safety Authority, 2012b).
*JEFCA - Joint FAO/WHO Expert Committee on Food Additives.

4. Discussion

This mixed method study aimed for a holistic exploration of the development of a novel seaweed kombucha product in rural Iceland. Like any study, it had several limitations, but overall this research adds important knowledge on the Icelandic context to the scholarly and applied discussions of seaweed products in the blue economy. The research also outlines aspects to be considered when including seaweed as either a flavour or functional ingredient. In the taste test, none of the participants reported a strong dislike for any of the kombucha samples and there were no statistically significant differences in preferences between the three kombucha types related to nationalities, age or education. However, it is important to underline the possibility of voluntary response sampling leading to biased results, and specifically “demand characteristics,” where participants respond in line with what they believe the researcher is exploring (Frampton, 2020). By design, the research took place in a small town where many people were already aware of the project because one of the research goals was to explore innovation in the blue economy in rural areas. However, the market for any potential product would always have to include the capital region, where one third of the population of Iceland resides. This research employed a simple taste test as a first step in understanding preferences for seaweed kombucha, but further market research is needed.

Although the taste test data suggest that kombucha is not well known amongst Icelanders, and a portion of those who took part in the taste tests likely self-selected to participate because they knew of kombucha, the fact remains that the high level of soft drink consumption, high preference for buying local products, and interest in healthier fizzy drink options as reported in the survey during the taste test indicate there is market potential for kombucha as an alternative to other soft drinks. Furthermore, the mean average of the amounts that participants were willing to pay for kombucha in the taste test (1496 ISK/L), is fairly similar to the mean price per litre for kombucha available in grocery shops (1169–1478 ISK). This can be seen as a positive result for the innovation aspect of this study and justifies the need for further market research.

A second limitation of the taste test however was that no sensory analysis was employed, thus any potential underlying reasons between sensory differences in the samples were not explored through the survey or study itself. This is an aspect that could be adapted and implemented in further research projects. In order to perform a sensory analysis, there would be the need for a specialized and trained sensory panel (Gengler, 2009). Sensory analysis could be useful to ascertain what differences respondents found in the different samples and even more so because there is a lack of focus and studies into sensory analysis on kombucha (Kim and Adhikari, 2020).

In terms of functional properties and food safety, the analysis of wild seaweed samples suggests that for seaweed from the Westfjords to be used as a functional ingredient, snack, or food additive, testing and further research is needed on seaweed to ascertain heavy metal and iodine limits. There were potential concerns for arsenic from two sites (Ósvör and þingeyri), which is a potential barrier to human consumption. The Westfjords are known to have higher naturally occurring levels of cadmium and arsenic due to the volcanic bedrock (Halldórsson, H.P., personal communication, January 2021; Hixson, 2019) In light of this information, it would also be valuable to assess inorganic arsenic concentrations to better assess the associated risk. Iodine levels were also high for sugar kelp from þingeyri; for example only 0.2 g of dried sugar kelp from þingeyri would be needed to fulfil the upper tolerable daily limit (600 μg; Scientific Committee on Food of European Commission, 2002). All samples were above the French recommendations for the maximum level of cadmium, which could lead to excess exposure depending on seaweed use, preparation and the frequency and amounts consumed. It should be noted that these limits and calculations would also have to take in to account an individual's diet.

Another limitation of the study was the geographic and seasonal scope of the heavy metal sampling. Due to budget limitations, testing for seasonality of seaweed ingredients was restricted in this study, but these tests would become important in later phases of kombucha production. For the use of seaweed in any food, it is beneficial to ascertain seasonal variations of compounds within the seaweed tissue, both undesirable (toxins, etc.) as well as beneficial ingredients with positive nutritive properties. In regard to heavy metals, concentrations for the most part are dependent upon the growing area (Roleda et al., 2019), but seasonal variations in cadmium and iodine levels have been documented, with highs and lows in late winter and summer respectively (Riget et al., 1995; Sá Monteiro et al., 2019). Beyond toxicity, questions remain regarding how seaweed reproduction cycles and growth patterns affect concentrations of different compounds. Studies have explored the seasonality of mannitol levels in Iceland (Sjotun and Gunnarsson, 1995). Furthermore, optimal harvesting times related to sugar kelp were highlighted as being in May, June and potentially July (Valsdóttir and Sturluson, 2014). Studies have also referred to how sugar kelp can be enjoyable due to its elevated carbohydrate levels (Stefaniak–Vidarsson et al., 2019), whilst other studies have also focused on glutamic acid, aspartic acid, and proteins (Galland-Irmouli et al., 1999). More research on seasonal variations and optimal harvesting times for taste and nutritional value is needed in general for all novel and developing seaweed food products, including the unique process of making seaweed infusions for kombucha.

Regarding the low levels of heavy metals and iodine in the kombucha samples, this could be due to numerous factors, such as the low amounts of seaweed used per L and also due to the fact that the seaweed infusion was performed at room temperature and in fresh water. Temperature is an important factor in terms of iodine (Stévant et al., 2018) and arsenic concentration (Park et al., 2018) because letting seaweed sit in liquid can cause elements to transfer from the seaweed to the liquid, with variations due to the technique used (Mouritsen et al., 2013). Other techniques exist to reduce certain levels of unwanted elements such as blanching to reduce iodine levels (Nielsen et al., 2020) and heat treatment to reduce arsenic levels (Park et al., 2018). However, these techniques could also lead to lower levels of glutamic and alanine acids and minerals, as well as affect the taste and texture and antioxidant properties of different seaweed products (Nielsen et al., 2020). As such these techniques to reduce iodine and heavy metals could be researched further and also include sensory analysis tests and evaluation of consumer preferences, not only for kombucha, but also for seaweed as a snack and culinary ingredient.

Finally, one important finding of this research was the extent to which the unclarity surrounding Icelandic regulations on heavy metal and iodine content could impact potential blue economy entrepreneurs. The lack of regulations is known in the European and Nordic context (see Hogstad et al., 2022) but for a start-up company, this can be a difficult world to navigate. Due to the lack of formal national seaweed consumption regulations in Iceland, EU regulations and EFSA tolerable intake levels are used as reference points to determine safe levels for products that are destined for the Icelandic consumer market (Jónsdóttir, I., personal communication, February 5, 2021). Although MAST states that EFSA opinions on arsenic and iodine are not regulations, there have been instances where products such as food supplements have been removed from the market due to iodine levels exceeding the upper tolerable limit of 600 μg (Matvælastofnun, 2020). However, when cases are judged on an individual basis, there is no clear framework to easily understand where the boundaries and limits lie, and this can be confusing even for researchers and certainly for blue economy entrepreneurs. Projected development within the global seaweed industry means that heavy metal issues need to be understood, investigated and addressed (Bouga and Combet, 2015; Roohinejad et al., 2017), and this is true for Iceland as well. Overall safety is a key aspect, where consumers' trust in regard to safety is not only anchored in businesses and companies involved with food, but also with the governmental bodies that are tasked with assessing and reviewing safety issues in regard to food (Wilcock et al., 2004). In addition to consumer safety, the producers – in this case entrepreneurs in the food industry, chefs, seaweed farmers, and so on – need stability and transparency in the regulatory environment. Any changes in decisions from EFSAs monitoring recommendations, particularly for arsenic and iodine, could potentially change the innovation atmosphere for many aspects of the food production industry.

5. Conclusion

Kombucha production has developed into a profitable industry, and although the kombucha market in Iceland is still in its early stages, this study shows that seaweed kombucha is a feasible prospect for Icelandic consumers. Although kombucha processes are well documented, there are specific considerations when including seaweed as either a flavour or a functional ingredient and this research also explored the combination of other flavours along with the seaweed infusions. More research is warranted on market feasibility regarding domestic and international markets and the impacts of seasonal seaweed growth patterns on taste and nutritional quality, but this study documented that a local seaweed kombucha product would be feasible both in terms of safety and commercial potential. This research provides findings from the first published study on consumer perception of seaweed kombucha in the Icelandic context. Taste test results showed that awareness of kombucha is low, and there was no significant preference between seaweed kombucha and non-seaweed kombucha. The survey also gathered important information for future entrepreneurs and researchers on perceptions of fizzy drinks, health drinks, and seaweed products in general. From the perspective of heavy metal and iodine content, the low levels found in the kombucha product are a positive indicator, meaning exposure and any related health risks would be low. However, this study highlights that further research is needed for direct consumption of seaweed for the species obtained in the Westfjords due to the levels of arsenic, cadmium and iodine, particularly in sugar kelp. Furthermore, food safety regulations need to be clarified and standardized before seaweed products can be fully integrated into the Icelandic market. Future market research should focus on a nation-wide understanding of Icelandic consumer preference for seaweed kombucha products, in addition to detailed sensory evaluation studies. This paper contributes to both the researchers and practitioners exploring the obstacles and opportunities in Iceland's growing blue economy.

Implications for gastronomy

Seaweed products are a rapidly increasing topic of interest in gastronomy from many angles, such as products, methods, food safety and culinary trends. This research used a mixed methods approach and findings are relevant for culinary applications because the paper includes detailed processes for seaweed kombucha production. Although kombucha processes are well-documented, there are specific considerations when including seaweed as either a flavor or a functional ingredient. This paper also discusses including the combination of other flavors along with the seaweed infusions.

A second method related to food safety considerations specifically for heavy metals in seaweed products provides context for other chefs and researchers. Heavy metal testing and limits for seaweed products are not standardized in Iceland and this paper outlines the major "need to know" aspects in this regard. How the seaweed is harvested and treated is a topic of conversation, and the timing of heavy metal tests in the food preparation process are also of importance.

Finally, this research provides findings from a first study in consumer perception of seaweed kombucha in the Icelandic context. Although it was a simple taste test on kombucha products, the survey also gathered information on perceptions of fizzy drinks, health drinks, and seaweed products in general. This is the kind of research that can be shared with future chefs and researchers in a larger context.

CRediT authorship contribution statement

Martyn Jones: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Catherine Chambers:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Peter Krost:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

None.

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Data availability

Heavy metal data are shared in the manuscript, but aggregate survey data are available upon request.

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