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Review article

Volatile compounds of six species of edible seaweed: A review

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ABSTRACT

Seaweeds are widely distributed throughout the world. Many seaweeds are of commercial importance with some consumed directly or used as an ingredient as they have functional, nutritional and/or organoleptic properties. Consumer acceptance of food is closely related to its sensory properties, of which flavor is of prime importance. A significant contributor to flavor is the aromatic volatile components present. This review focusses on the volatile components identified in commercially important edible macroalgae species consisting of four brown (*Himanthalia elongata*, *Laminaria* spp. including *L. ochroleuca*, and *Undaria pinnatifida*) and two red species (*Porphyra umbilicalis* and *Palmaria palmata*). In excess of 200 volatile compounds have been identified consisting of hydrocarbons, alcohols, aldehydes, ketones, acids, esters, furans, phenols and sulfur- containing compounds, among others present in minor quantities. The extraction/concentration conditions, chromatography and detection methodologies applied varied and impacted on the volatiles identified due to differences in their hydrophobicity, molecular weight and vapor pressure. This review highlights that considerable more information is required to identify volatile aromatic compounds in edible macroalgae and to identify those most likely to impact sensory perception. Such information could be used to aid new product development or widen applications of these seaweeds in the food or beverage sectors.

1. Introduction

Seaweed or macroalgae are a large diverse group of macroscopic, eukaryotic, photosynthetic, marine organisms. Ten thousand different species have been described to date [1]. According to their pigmentation, seaweeds are classified into three higher taxa, which include brown seaweed (Phaeophyceae), green seaweed (Chlorophyceae), and red seaweed (Rhodophyceae) [2]. Seaweeds compose a credible source of functional ingredients with bioactive and volatile aromatic compounds [3]. There are currently 15–20 species of edible seaweed commercially available for consumption in Europe [4]. Seaweeds are widely consumed, especially in Asian countries, fresh, dried, or as ingredients in prepared foods [5]. They represent a food group that is not normally ingested in unprocessed form in Western societies, where algae remain of minor importance in spite of proven nutritional benefits [6].

Researchers worldwide have placed great importance on the chemical composition and bioactive components in seaweeds [7,8]. Their use as functional ingredients has instigated new developments in food processing [9,10], one of which is in meat product formulation [5]. Seaweeds have significant potential for use in processed foods as they can provide strong odors and characteristic marine flavors [11]. Researchers have also investigated the volatile fraction of some edible seaweed species, generally via gas chromatography mass spectrometry (GC–MS). Volatile compounds from macroalgae can be extracted utilizing several processes, the aim of which is to obtain an aromatic profile of the species in fresh or processed form [12]. The extraction and concentration of volatile compounds from seaweeds has been conducted using headspace solid-phase microextraction (HS-SPME) [13,14], dynamic headspace extraction (DHE) [11] and static headspace extraction (SHE) [15], simultaneous distillation-extraction (SDE) [16], supercritical fluid extraction (SFE) [17], pressurized solvent extraction (PSE) [18], multiple headspace sorptive extraction (MHSSE) [19] and pre-evaporation [20]. It is well established that even though multiple extraction techniques are available for the analysis of volatile organic compounds none as yet can provide a complete volatile profile as each has inherent bias for certain chemical classes based on volatility, polarity, vapor pressure and molecular weight [12].

Consumers' acceptance of food is intimately related to its flavor. Therefore, volatile components are very important parameters in food quality and flavor [11]. Volatile organic compounds are molecules with high vapor pressure, moderate hydrophilicity and low molecular

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weight. Hydrocarbons, ketones, aldehydes, alcohols, carboxylic acids, esters, halogenated compounds, sulfur compounds, furans, pyrazines, pyridines, amines and other volatile compounds comprise a broad range of volatile metabolites present in seaweeds [21]. There are significant differences in volatile compounds between seaweed species. The species, its geographical origin and processing parameters are known to influence its volatile profile [22].

The main aim of this review is to provide insights into the volatile analyses of six commercially important brown and red seaweed species used in the food industry. The most widely harvested, due to their abundance and accessibility, are the brown *Laminaria* spp. and the red *Palmaria palmata* seaweeds. This review focuses on the volatile fraction of edible seaweeds belonging to four species (*Himanthalia elongata*, *Laminaria* spp. including *Laminaria ochroleuca*, and *Undaria pinnatifida*) of brown seaweed, and two species (*Porphyra umbilicalis* and *Palmaria palmata*) of red seaweed due to their presence in Irish waters [23,24]. A data search using the major databases (PubMed, ScienceDirect, Springerlink, ResearchGate) with the keywords ("macroalgae", "seaweeds", "volatile compounds", "brown kelp", "*Himanthalia elongata*", "*Laminaria japonica*", "*Laminaria ochroleuca*", "*Palmaria palmata*", "*Porphyra umbilicalis*", "*Undaria pinnatifida*", "Winged kelp") highlighted that there is a lack of information on the volatile compounds for these seaweed species and therefore this review is timely as it provides a relevant summary of up to date information.

2. Sensory properties of seaweed volatile compounds

Volatile compounds perceived simultaneously define the odor of a food product [25]. Over 10,000 volatile compounds have been detected in foods, but only a few hundred (5–10%) have any significance as odor compounds [26]. Key odor compounds have odor threshold values in a very broad range (mg/l – pg/l) and two key odor features, odor threshold and compound concentration, must be taken into account when discussing the odor impact of compounds in foods [26]. The odor activity value (OAV) estimates the importance of a flavor compound in a food, based on the ratio of its concentration to its odor threshold concentration in that food. Only compounds which exceed the threshold level in a food will impact on flavor and thus sensory perception [25]. Conceptually, the larger the OAV, the more likely that compound will contribute to the overall odor of a complex odor mixture [27].Compounds with extremely low odor thresholds, even when present in very low concentrations, can be important odorants [26]. Gas chromatography-olfactometry (GC-O) is the main approach used to study the impact of volatile compounds on sensory perception.

Some analytes with sensory significance present in a food are at low concentrations, therefore they require isolation and concentration from the food prior to analysis [28]. The presence of trace quantities of odor components complicates the extraction/concentration process, to the extent that methods based on volatility, solubility and the use of organic solvents will also extract water, lipids, proteins and carbohydrates, respectively that may necessitate further processing prior to analysis by GC–MS. Odor isolation is difficult because volatiles have a very low molecular mass ($<$ 300 Da) and belong to a large number of different chemical classes [28]. In relation to the different volatile chemical classes identified in these seaweeds, the most abundant were, in decreasing order, hydrocarbons, ketones, aldehydes, alcohols, esters, halogenated compounds, carboxylic acids, furans, phenols, sulfur compounds, pyrazines, pyridines, amines and some miscellaneous compounds.

Terpenes are potentially important odor compounds, where sesquiterpene hydrocarbons have lower impact than monoterpenes due to their higher detection thresholds [29]. Hydrocarbons are not always relevant to the aroma because of their high odor detection thresholds, but compounds with high odor thresholds can also play an essential role in food aroma when present at high concentrations [30]. Ketones are potentially important odor compounds due to their abundance and odor activity. Ketones, such as β-ionone and 6-methyl-5-hepten-2-one, are potent odorant in seafood contributing to the aroma composition of seaweeds [31]. The chain length of aldehydes mostly affects odor thresholds and odor properties. Aldehydes with low molecular weight ($<$ 150 Da) tend to be associated with unpleasant odors, and those with higher molecular weights tend to have sweet, fruity odors [26]. Aldehydes are important aroma compounds because of their low odor threshold values [32]. Carbonyl compounds and aldehydes are responsible for various odorant notes such as the nutty alcoholic odor of acetaldehyde [33] and the almond odor of benzaldehyde [29]. Branched-chain alcohols are known to have low odor threshold values, therefore may significantly contribute to odor [32]. As the ability of alcohols to dissolve in water decreases the odor threshold increases. Therefore unsaturated alcohols have a greater impact on food flavor than saturated alcohols [26]. Halogenated compounds are mainly isolated from red and brown seaweeds [2]. Halogenated compounds substituted with a halogen moiety at the ortho position interact strongly with human odor receptors, resulting in high odor activities [34]. Aryl halides are fairly pleasant smelling liquids, but arylmethyl (benzylic) halides are irritating to nasal passages [35]. Acids may increase and enhance food characteristic odor profiles. The strength of odor decreases with increasing acid chain length. Simple acids, with $<$ 6 carbon atoms, have high odor thresholds, while long chain acids, with 12 or more carbon atoms, are odorless. Unsaturated acids generally have sharper and stronger odors than saturated ones [26]. Esters present mainly fruity notes (e.g. apple odor of butyl acetate) and unsaturated esters have lower thresholds than saturated ones [29]. Furans consist of a family of important chemicals in the formation of crab flavor [36]. Lipoxygenase-catalysed oxidation of linoleic acid can produce 2-pentyl furan which has been associated with 'earthy', 'beany' odor notes [37]. Sulfur compounds are present in very low amounts and possess very low odor thresholds. They are present mainly in brassica vegetables as, for example, dimethyl sulfide responsible for cabbage odor [26]. Many pyrazines have intensive odors and very low odor thresholds. Therefore, these compounds contribute to many odors and flavors [38]. Heterocycles, in the pyridines group, are the main compounds of caramel odor [39]. Amines have a strong ammoniac-like odor. Amines are formed from Strecker degradation products, and their odors depend on the pH value [29]. Phenolic compounds contribute to the flavor of many foods [40].

The physicochemical properties of these compounds play a major role in sensory perception. Odor thresholds for particular compounds published in the literature can vary extensively and thus it is difficult to estimate an average odor threshold value based on literature data alone [26] (Table 1).

3. Key volatiles identified in commercially important seaweed species

3.1. Extraction and analytical methods

The major volatile components identified in commercially important seaweeds that likely have an impact on sensory perception are briefly summarized. The extraction/concentration conditions and polarity of the GC columns and methods of detection varied between studies [10,12,17,20,41,42].

López-Pérez et al. [22] used HS-SPME GC–MS with a divinylbenzene/carboxen/polydimethylsiloxane (DVB/CAR/PDMS) SPME fiber to identify volatiles in dried samples of five of the six seaweeds reviewed in this study (*H. elongata*, *U. pinnatifida*, *L. ochroleuca*, *P. umbilicalis* and *P. palmata*). These authors optimized the extraction/concentration conditions (equilibration time, extraction time and temperature and sample size to headspace volume ratio) and were able to identify a large number of volatiles compounds. They used a polyethylene glycol highly polar column and a single quadrupole MS over the mass range of 35 to 300 *m/z*.

Table 1

Volatile compounds found in four brown and two red species of edible seaweed.

Compound	*Himanthalia elongata*	*Laminaria* spp.		*Undaria pinnatifida*	*Palmaria palmata*	*Porphyra umbilicalis*	Aroma threshold
		Laminaria spp.	*Laminaria ochroleuca*				
Hydrocarbons							
Butane[c]		✓		✓			0.421–5048 ppm[g]
Hexane[c]		✓		✓			30–248 ppm[g]
Octane[a]	✓		✓	✓	✓	✓	0.66–235 ppm[g]
Nonane[a]	✓		✓	✓	✓	✓	2.3–21 ppm[g]
Undecane[e]				✓			
Dodecane[e]				✓			
Tetradecane[e]				✓			
Pentadecane[a,e]	✓		✓	✓	✓	✓	
Hexadecane[e]				✓			
Heptadecane[a,e]	✓			✓	✓	✓	
Octadecane[e]				✓			
6-Methylpentadecane[e]				✓			
2-Methylheptane[a]	✓		✓	✓	✓	✓	
4-Methylheptane[a]	✓		✓	✓	✓	✓	
4-Methyloctane[a]	✓		✓	✓	✓	✓	
2-Methylnonane[a]	✓		✓	✓	✓	✓	
4-Methyldecane[a]	✓		✓	✓	✓	✓	
5-Methyldecane[a]	✓		✓	✓	✓	✓	
2-Methylundecane[a]	✓		✓	✓	✓	✓	
3-Methylundecane[a]	✓		✓	✓	✓	✓	
4-Ethyldecane[a]	✓		✓	✓	✓	✓	
2,4-Dimethylhexane[a]	✓		✓	✓	✓	✓	
2,4-Dimethylheptane[a]	✓		✓	✓	✓	✓	
2,7-Dimethyloctane[a]	✓			✓	✓	✓	
2,5-Dimethylnonane[a]	✓		✓	✓	✓		
3,7-Dimethyldecane[a]	✓		✓	✓	✓	✓	
2,4-Dimethylundecane[a]	✓		✓	✓	✓	✓	
2,6-Dimethylundecane[a]	✓		✓	✓	✓	✓	
4,4-Dimethylundecane[a]	✓		✓	✓	✓	✓	
4,8-Dimethylundecane[a]	✓		✓	✓	✓	✓	
4,6-Dimethyldodecane[a]	✓			✓	✓	✓	
2,4,6-Trimethyloctane[a]	✓			✓	✓		
2,6,10-Trimethyl-tetradecane[e]				✓			
Cyclopentane, iodo[c]		✓					
Cyclododecane[b,c]	✓			✓			
Dicloromethane[c]		✓		✓			
Trichloromethane[c]		✓					
(E)-2-Octene[a]	✓		✓	✓	✓	✓	
2,4-Dimethyl-1-heptene[a]	✓		✓	✓	✓	✓	
1,4-Octadiene[a]	✓		✓	✓	✓	✓	
1,3-(*E*)-5-(*Z*)-Octatriene[f]					✓		
1,3-Cyclooctadiene[a]	✓		✓	✓	✓	✓	
Trimethyl-1,3-cyclopentadiene[f]					✓		
1,5-Heptadien-3-yne[e]				✓			
2-Methyl-1-hexen-3-yne[e]				✓			
3-Ethyl-2-methyl-1,3-hexadiene[a]	✓		✓	✓	✓	✓	
3-Ethylidene-1-methylcyclopentene[f]					✓		
2-(Chloromethyl)-1-butene[c]		✓					
1,3-Dimethylbenzene[a]	✓			✓	✓	✓	
1,2,3-Trimethylbenzene[a]	✓			✓	✓	✓	
1,2,4-Trimethylbenzene[f]					✓		
Ketones							
2-Propanone[a]	✓		✓	✓	✓	✓	40–476 ppm[h,j]
2-Butanone[a]	✓		✓	✓	✓	✓	n/a[h]
2-Pentanone[a]	✓		✓	✓	✓	✓	70 ppb[h,j]
3-Hexanone[a]	✓		✓	✓	✓	✓	41–81 ppb[h,j]
2-Heptanone[a]	✓		✓	✓	✓	✓	1 ppb-1.33 ppm[h,j] 2.66–3.73 ppm[h,k]
2-Octanone[a]	✓		✓	✓	✓	✓	41–62 ppb[h,j]
3-Octanone[d]		✓			✓		21–50 ppb[h,j]
1-Penten-3-one[c]				✓			1–13 ppb[h,j]
3-Penten-2-one[a]	✓		✓	✓	✓	✓	1.5 ppb[h,j]
1-Octen-3-one[a]	✓			✓	✓	✓	0.05–4 ppb[h,j]
3-Octen-2-one[a]	✓			✓	✓	✓	n/a[h]
2,3-Butanedione[a]	✓		✓	✓	✓	✓	1–8.6 ppb[i]
2,5-Octadione[a]	✓		✓	✓	✓	✓	
(Z,E)-3,5-Octadien-2-one[a]	✓		✓	✓	✓	✓	
(E,E)-3,5-Octadien-2-one[a,e]	✓		✓	✓	✓	✓	0.15 ppm[h,j]
5,9-Undecadien-2-one, 6, 10-dimethyl-, (z)[e]				✓			60 ppb–6.4 ppm[h,j]
3,5-Dimethyl-2,7-octadione[a]	✓		✓	✓	✓	✓	

(*continued on next page*)

Table 1 (*continued*)

Compound	*Himanthalia elongata*	*Laminaria* spp.		*Undaria pinnatifida*	*Palmaria palmata*	*Porphyra umbilicalis*	Aroma threshold
		Laminaria spp.	*Laminaria ochroleuca*				
1,3-Cyclohexanedione,2-(2-propenyl)-[e]				✓			
4,4-Dimethyl-2-cyclohexen-1-one[e]				✓			
2(1H)-naphthalenone, octahydro-8a-methyl-, trans-[e]				✓			
6-Methyl-3,5-heptadien-2-one[a]	✓		✓	✓	✓	✓	375 ppb[h,j]
6-Methyl-5-hepten-2-one[a]	✓		✓	✓	✓	✓	50 ppb[h,j]
1-Hydroxy-2-propanone[a]	✓			✓	✓	✓	
3-Hydroxy-2-butanone[a]	✓		✓	✓	✓		
2,2,6-Trimethylcyclohexanone[a,e]	✓			✓	✓	✓	100 ppb[h,j] 310 ppb[h,k]
3,5,5-Trimethyl-2-cyclohexen-1-one[a]	✓		✓	✓	✓	✓	
2-Propyl-2-cyclohexenone[a]				✓	✓	✓	
γ-Valerolactone[a]	✓		✓	✓	✓	✓	n/a[h]
γ-Butyrolactone[a]	✓		✓	✓	✓	✓	20–50 ppm[h,j]
1-Phenylethanone[a]	✓		✓	✓	✓	✓	170 ppb[h,j] 2.9 ppm[h,k]
γ-Hexalactone[a]	✓		✓	✓	✓	✓	1.6 ppm[h,j]
5-Ethyl-2(5H)-furanone[a]	✓		✓	✓	✓	✓	
Isophorone[e]				✓			0.20 ppm[h,j]
4-Ketoisophorone[a]	✓		✓	✓	✓	✓	n/a[h]
α-Ionone[a]				✓	✓	✓	0.6–10 ppb[h,j]
β-Ionone[a,e]	✓		✓	✓	✓	✓	0.007–205 ppb[h,j]
Trans-β-ionone[a]	✓		✓	✓	✓	✓	
7,8-Epoxy-α-ionone[a]	✓				✓	✓	
1-(4-Acetylphenyl)-ethanone[a]	✓		✓	✓	✓	✓	
Methylethylmaleimide[a]			✓	✓	✓	✓	
Dihydroactinidiolide[a]	✓		✓	✓	✓	✓	
Aldehydes							
Ethanal[a]	✓		✓	✓	✓	✓	0.7–200 ppb[h,j] 27–380 ppb[h,k]
Propanal[a]	✓		✓	✓	✓	✓	9.5–35 ppb[h,j]
Butanal[a,c]	✓	✓	✓	✓	✓	✓	19–37 ppb[h,j] 11–27 ppb[h,k]
Pentanal[a,d]	✓	✓	✓	✓	✓	✓	12–100 ppb[h,j]
Hexanal[a,c,d,e]	✓	✓	✓	✓	✓	✓	4.1–22.8 ppb[h,j] 400 ppb[h,k]
Heptanal[a,d,e]	✓	✓	✓	✓	✓	✓	3–60 ppb[h,j]
Octanal[a,c,e]	✓	✓	✓	✓	✓	✓	1.4–6.4 ppb[h,j]
Nonanal[a,c,d,e]	✓	✓	✓	✓	✓	✓	1–8 ppb[h,j]
Decanal[c]		✓		✓		✓	0.1-6 ppb[h,j] 9 ppb[h,k]
Undecanal[c]		✓					0.4–100 ppb[h,j]
Dodecanal[c]		✓					0.5–1.5 ppb[h,j]
(E)-2-Butenal[a]	✓		✓	✓	✓	✓	525 ppb[i,j]
(E)-2-Pentenal[a,c,e]		✓	✓	✓	✓	✓	1.5 ppb[h,j]
(E)-2-Hexenal[a,d,e]	✓	✓	✓	✓	✓	✓	17 ppb–10 ppm[i,j]
(E)-2-Heptenal[a,e]	✓	✓	✓	✓	✓	✓	13–51 ppb[j]
(Z)-4-Heptenal[a]	✓		✓	✓	✓	✓	0.4 ppb[h,j]
(E)-2-Octenal[a,d,e]	✓	✓	✓	✓	✓	✓	3–4 ppb[h,j]
(E)-2-Nonenal[d,e]		✓		✓			0.1 ppb[h,j]
(E)-2-Decenal[d,e]		✓		✓			1 ppb[h,j]
(E,E)-2,4-Heptadienal[a,c]	✓		✓	✓	✓	✓	n/a[h]
(Z,E)-2,4-Heptadienal[a]	✓		✓	✓	✓	✓	3.6 ppm[i,j]
(E,E)-2,6-Nonadienal[a]	✓		✓	✓	✓	✓	0.09 ppb[h,j]
(E,Z)-2,6-Nonadienal[e]				✓			
(E,E)-2,4-Decadienal[e]				✓			0.07–10 ppb[h,j]
(3Z)-3-Hexenal[c]				✓			0.25 ppb[h,j]
5-Hexenal[c]		✓					
2-Methylbutanal[a]			✓	✓	✓	✓	0.15–140 ppb[i,j]
3-Methylbutanal[a,d]	✓	✓	✓	✓	✓	✓	12 ppb[i,j]
(E)-2-Methyl-2-butenal[a]			✓	✓	✓	✓	500 ppb[h,j]
2-Methyl-2-propenal[a]					✓	✓	
2-Methyl-2-pentenal[a]				✓	✓	✓	290 ppb[h,k]
2,2-Dimethylpropanal[f]					✓		
Benzaldehyde[a]	✓		✓	✓	✓	✓	100 ppb – 4.6 ppm[h,j] 330 ppb–4.1 ppm[h,k]
4-Ethylbenzaldehyde[a]	✓		✓	✓	✓	✓	13 ppb[h,j]; 40 ppb[h,k]
4-Propylbenzaldehyde[a]	✓		✓	✓	✓	✓	
β-Cyclocitral[a,e]	✓		✓	✓	✓	✓	
Safranal[a]	✓		✓	✓	✓	✓	
Alcohols							

(*continued on next page*)

Table 1 (*continued*)

Compound	*Himanthalia elongata*	*Laminaria* spp.		*Undaria pinnatifida*	*Palmaria palmata*	*Porphyra umbilicalis*	Aroma threshold
		Laminaria spp.	*Laminaria ochroleuca*				
Ethanol[c]		✓		✓			8–900 ppb[h,j]
1-Propanol[c]		✓		✓	✓	✓	3.2–7500 ppm[i]
1-Butanol[d]		✓					500 ppb–509 ppm[h,j]
1-Pentanol[a]	✓		✓	✓			32 mg/L liquid[i]
3-Pentanol[a]	✓		✓	✓	✓	✓	
1-Hexanol[a,c]	✓	✓	✓	✓	✓	✓	0.01–5.2 ppm[i]
1-Octanol[a]	✓		✓	✓	✓	✓	42–480 ppb[h,j]
3-Decanol[e]				✓			79–410 ppb[h,j]
1-Penten-3-ol[a,c,d]	✓	✓	✓	✓	✓	✓	400 ppb[h,j]
(E)-2-Penten-1-ol[a]	✓		✓	✓	✓	✓	
(Z)-2-Penten-1-ol[a,c]	✓	✓	✓	✓	✓	✓	
3-Hexen-1-ol[c]		✓		✓			70 ppb[h,j]
5-Hexen-1-ol[c]				✓			
(2E)-2-Hexen-1-ol[c]				✓			
1-Octen-3-ol[a,c,d]	✓	✓	✓	✓	✓	✓	14 ppb[h,j]; 25 ppb[h,k]
2-Octen-1-ol[a]	✓		✓	✓	✓	✓	40–840 ppb[h,j] 100 ppb[h,k]
(E)-2-Octen-1-ol[d]		✓					n/a[h]
(E)-2-Nonen-1-ol[d]		✓					130 ppb[h,j]
2,3-Butanediol[a]				✓			
(Z)-1,5-Octadien-3-ol[a]	✓		✓	✓	✓	✓	
1,7-Octadien-3-ol[a]	✓		✓	✓			
3,5-Octadien-2-ol[a]	✓		✓	✓	✓		
3-Methylbutanol[f]					✓		250 ppb–4.1 ppm[h,j]
2-Methyl-3-pentanol[a]	✓		✓	✓	✓		
(E)-2-Ethyl-1-hexanol[a]	✓		✓	✓	✓		n/a[h]
(Z)-2-Ethyl-1-hexanol[a]	✓						n/a[h]
2-(2-Methoxypropoxy)-1-propanol[a]	✓		✓	✓	✓	✓	
1-(2-Methoxypropoxy)-2-propanol[a]	✓		✓	✓	✓	✓	
1-(2-Methoxy-1-methylethoxy)-2-propanol[a]	✓		✓	✓	✓	✓	
1-Ethoxy-2-propanol[a]	✓		✓	✓	✓	✓	
Cyclooctanol[a]	✓			✓	✓	✓	
1,2-Dimethyl-cyclohexanol[a]	✓		✓	✓	✓	✓	
2,4-Dimethyl-cyclohexanol[e]				✓			
4,4-Dimethyl-cyclohex-2-en-1-ol[e]				✓			
Benzenemethanol[a]	✓		✓	✓	✓	✓	1.2–1000 ppb – 10–1000 ppm[h,j]
Halogenated compounds							
Iodo-methane[a]			✓		✓		
Iodo-ethane[a]			✓		✓		
2-Iodo-propane[a,c]		✓	✓	✓	✓		
1-Iodo-pentane[a,c]	✓		✓	✓	✓		
1-Iodo-octane[d]		✓	✓				
2-Fluoroprop-1-ene[f]					✓		
Chlorobenzene[f]					✓		0.21 ppm[i]
Dichloromethane[f]					✓		210–214 ppm[i]
Tribromomethane[d]		✓			✓		4.8×10^8 molecules/cc[i]
Trichloromethane[d]		✓			✓		
5-Chloro-1-pentene[a]			✓				
Carboxylic acids							
Ethanoic acid[a]	✓		✓	✓	✓	✓	10–522 ppm[j] 60 ppm[h,k]
Butanoic acid[a]	✓		✓	✓	✓	✓	240 ppb–4.8 ppm[h,j]
Hexanoic acid[a]	✓		✓	✓	✓	✓	93 ppb–10 ppm[h,j]
Heptanoic acid[a]	✓		✓	✓	✓	✓	640 ppb–10.4 ppm[h,j]
Octanoic acid[a]	✓		✓	✓	✓	✓	910 ppb–19 ppm[h,j]
2-Methylpropanoic acid[a]	✓		✓	✓		✓	10 ppb–9.5 ppm[h,j]
3-Methylbutanoic acid[a]	✓		✓	✓	✓	✓	
Esters							
Acetic acid ethyl ester[c]				✓			5 ppb–5 ppm[h,j]
Lactic acid ethyl ester[a]				✓			50–250 ppm[h,j]
Octyl benzoate[e]				✓			
Propanoic acid, 2-methyl-0.1-(1,1-dimethylethyl)-2-methyl-1,3,-propanediyl ester[e]				✓			
Hexanedioic acid, bis(2-methylpropyl) ester[e]				✓			n/a[h]
Dodecanoic acid, 1-methyl ester (isopropyl laurate)[e]				✓			n/a[h]
Pentanedioic acid, dibutylester[c]		✓		✓			
Phthalic acid, diisobutylester[e]				✓			
1,2,3-Propanetriol[a] triethanoate				✓			n/a[h]

(*continued on next page*)

Table 1 (*continued*)

Compound	*Himanthalia elongata*	*Laminaria* spp.		*Undaria pinnatifida*	*Palmaria palmata*	*Porphyra umbilicalis*	Aroma threshold
		Laminaria spp.	*Laminaria ochroleuca*				
1,2-Benzenedicarboxylic acid diethyl ester[a]	✓			✓	✓	✓	
Furans							
2-Ethylfuran[a,c,e]	✓		✓	✓	✓	✓	n/a[h]
2-Methylfuran[a]	✓		✓	✓	✓	✓	27 ppm[i]
2-Pentylfuran[a]	✓		✓	✓	✓	✓	6 ppb[h,j]
cis-2-(2-Pentenyl)furan[a]	✓		✓	✓	✓	✓	
Sulfur compounds							
Dimethyl sulfoxide[a]	✓		✓	✓	✓	✓	
Dimethyl sulfide[a]	✓		✓	✓	✓	✓	0.3–10 ppb[h,j]
Phenols							
Phenol,2,4-bis (1,1-dimethylethyl)-[b]	✓						
Phenol,2,6-bis (1,1-dimethylethyl)-4-methyl[b]	✓						
Amines							
N,*N*-Dimethyl-methanamine[a]	✓		✓		✓	✓	0.3–0.8 ppb[h,j] 500 ppb[h,k]
Pyrazines							
2,6-Dimethylpyrazine[a]			✓	✓			400–1500 ppb[h,j]
2,3,5,6-Tetramethylpyrazine[a]					✓		1–10 ppm[h,j]
Pyridines							
2-Ethylpyridine[a]				✓	✓		4–22 ppm[h,j]
Miscellaneous							
1-Acetyl-2,2-dimethylcyclobutane[a]			✓				
1,2-Benzisothiazole[e]				✓			
1,3-Cyclopentadiene, 5,5-dimethyl-2-ethyl-[e]				✓			
1-Methoxy-4-(1′-methylethyl)cyclohexa-1,4-diene[a]	✓		✓	✓	✓		
2,5-Dimethylhexane-2,5-dihydroperoxide[e]				✓			
2,7-Epoxy-megastigma-4,8-diene[a]	✓		✓	✓			
Stigmasta-5,24(28)dien-3-ol (Fucosterol)[a]	✓						

✓ Identified/Present in the seaweed.

Brown species: *Himanthalia elongata*, *Laminaria* spp., *Undaria pinnatifida*, *Laminaria ochroleuca*. Red species: *Palmaria palmata*, *Porphyra umbilicalis*.

[a] [22].

[b] [18].

[c] [11].

[d] [42].

[e] [13].

[f] [41].

[g] [52], diluent was assumed to be air, unless specified otherwise in the paper.

[h] [53], representative values in distilled water unless otherwise designated.

[i] [54], representative values in water unless otherwise designated.

[j] Detection.

[k] Recognition.

Balbas et al. [13] also used HS-SPME with a DVB/CAR/PDMS fiber, but incubated 0.5 g of dried sample (*U. pinnatifida*) for 30 min at 35 °C in a 10 mL headspace vial with 2 mL deionized water. The column was a 5% 1,4-bis(dimethylsiloxy)phenylene/95% dimethyl polysiloxane low polarity column. The mass scan of the single quadrupole MS was from *m/z* 48 to *m/z* 400.

Ferraces-Cascais et al. [11] used a purge and trap (sorbent not provided) to extract volatiles from fresh samples of two types of macroalgae (*Laminaria* spp. and *U. pinnatifida*) by a 5% diphenylpolysiloxane and 95% dimethyl-polysiloxane low polarity column with a single quadrupole MS, scanning a mass range of *m/z* 35–400. Le Pape et al. [41] also used purge and trap (Tenax TA 80–100 mesh) at 25 °C; and a polyethylene glycol highly polar column and a single quadrupole MS over the mass range 33–300 *m/z*.

Takahashi et al. [42] used a capillary column (no specifications) to extract volatiles from *Laminaria* spp. Plaza et al. [18] used simultaneous distillation and extraction under reduced pressure and an accelerated solvent extractor with hexane, ethanol and water as solvents to extract volatiles from *H. elongata*. The GC column was a fused silica capillary column coated with a 0.25 μm layer of 94% methyl, 5% phenyl, 1% vinyl polysilicone (low polarity), coupled to a quadrupole MS using a mass interval ranging from 35 to 450 *m/z*. These authors also optimized extraction conditions in terms of solvents and temperature.

3.2. Volatile compounds of seaweed species

3.2.1. Brown seaweed species

3.2.1.1. Himanthalia elongata (sea spaghetti). *Himanthalia elongata* or ‘sea spaghetti’ belongs to the Phaeophyta or brown macroalgae [43]. This edible brown seaweed is commonly harvested along the European side of the Atlantic Ocean [23]. It has a history of safe use and acceptability in cooking and was previously used to add a beefy or nutty-like flavor to dishes [43]. Indeed, beef patty formulations containing *H. elongata* seaweed were improved in texture and mouthfeel preserving their sensory quality, and were of the most overall accepted [44].

López-Pérez et al. [22] found 34 hydrocarbons in *H. elongata*, but only 30 could be positively identified. The most abundant branched-chain hydrocarbon was 4-ethyldecane and the most abundant linear saturated hydrocarbon was octane. Plaza et al. [18] only identified one hydrocarbon, cyclododecane, in *H. elongata*. López-Pérez et al. [22], identified 31 ketones; 2-propanone (acetone) predominated among linear saturated ketones, 3,5-octadien-2-one among linear unsaturated ketones and 3-hydroxy-2-butanone among branched-chain unsaturated ketones. *H. elongata* had the lowest concentration of volatile aldehydes of the seven seaweeds included in their study [22]. These same authors identified 22 aldehydes, with hexanal as the main linear saturated aldehyde, and (E)-2-hexenal as the main linear unsaturated aldehyde and benzaldehyde the main aromatic aldehyde. They also identified 22 volatile alcohols, with 1-(2-methoxypropoxy)-2-propanol the most abundant branched-chain alcohol, the most abundant linear unsaturated alcohols were 1-octen-3-ol and 1-penten-3-ol, with 1-pentanol as the most abundant linear saturated one. Only one halogenated compound (1-iodopentane), one ester (1,2-benzenedicarboxylic acid diethyl ester), and one amine (dimethylmethanamine) were detected in *H. elongata*. Seven carboxylic acids were also identified, the most abundant linear acid was ethanoic (acetic) acid, whereas the most abundant branched-chain acid was 3-methylbutanoate. Four furans were also detected; 2-methylfuran, cis-2-(2-pentenyl)furan, 2-ethylfuran and 2-pentyl-furan, with the latter two being the most predominant. Two sulfur compounds, dimethyl sulfide and dimethyl sulfoxide were also detected as were two dienes, 7-epoxy-megastigma-4,8-diene and 1-methoxy-4-(1′-methylethyl)cyclohexa-1,4-diene.

Plaza et al. [18] also identified two phenols; 2,4-bis-(1,1-dimethylethyl)- and phenol,2,6-bis-(1,1-dimethylethyl)-4-methyl; two fatty acids, tetradecanoic (myristic) and hexadecanoic (palmitic) acid; stigmasta-5,24(28)dien-3-ol (fucosterol) and cyclododecane in *H. elongata.* The volatile compounds identified in *H. elongata* can be found in Table 1.

3.2.1.2. *Laminaria spp.*

Laminaria spp. are members of brown algae, the most important seaweed cultured in the Pacific Ocean from the economical point of view [45]. The yearly output of this seaweed is approximately 15 million tons in dry weight [46]. At present, it is valued mainly as food and widely consumed in East Asia [47].

Ferraces-Casais et al. [11] identified 26 volatile compounds in *Laminaria* spp.; six were hydrocarbons, with butane the most abundant. The hydrocarbons constituted the second most abundant family of volatiles present. Alcohols were the most important class of volatile compounds identified (29% of compounds identified). Seven alcohols were identified with 1-penten-3-ol as the most predominant one. Takahashi et al. [42] also identified 1-penten-3-ol and 1-butanol in Kombu. Ten aldehydes were identified with hexanal the most abundant. Takahashi et al. [42] also identified pentanal, 2-(*E*)-hexenal, hexanal, heptanal, nonanal in Kombu. Pentanedioic acid, dibutylester was the only ester identified by Ferraces-Casais et al. [11]. Six halogenated compounds were also identified, among them 1-iodo-pentane and 2-iodo-propane. Takahashi et al. [42] found in addition iodopentane, trichloromethane and tribromomethane. The low amount of chemical classes identified is more likely due to the extraction method (purge and trap) employed in relation to the polarity of the compounds present. Takahashi et al. [42] studied volatile compounds of dried Kombu (*Laminaria* spp.) by SDE and DHE. The 49 volatiles of Kombu analyzed by DHE were almost the same as identified using SDE, except trichloromethane and tribromomethane were not detected by DHE, and 3-methylbutanal, (E)-2-octenal, (E)-2-decenal (aldehydes); (E)-2-octen-1-ol, (E)-2-nonen-1-ol (alcohols) and 1-iodo-octane (halogenated compound) were only present by DHE. Only 1-iodooctane had an odor from the 4 kinds of iodides detected. The volatile compounds identified in *Laminaria* spp. can be found in Table 1.

Laminaria ochroleuca belongs to brown algae (Filum Ochrophyta, Class Phaeophyceae of the family of Laminariaceae). *L. ochroleuca* specimens grow in subtidal areas (from Morocco to southern UK and in the Mediterranean), and are abundant in the Atlantic coast of Cadiz (Southern Spain) [51].

López-Pérez et al. [22] identified 128 volatile compounds in *L. ochroleuca*. The numbers varied from 30 hydrocarbons, to 26 aldehydes, 7 carboxylic acids, to none esters. Volatile ketones, alcohols and furans reached their lowest levels in *L. ochroleuca* compared to the other species studied. Twenty-seven ketones, 20 alcohols and 4 furans were identified. Total volatile halogenated compounds reached their highest in *L. ochroleuca*, which contained 6 halogenated compounds. The most abundant one was iodo-methane followed by 2- and 1-iodopentane. Other volatile compounds detected in *L. ochroleuca* were 1-acetyl-2,2-dimethylcyclobutane, 1-methoxy-4-(1′-methylethyl)cyclohexa-1,4-diene and 2,7-epoxy-megastigma-4,8-diene. A summary of the volatile compounds identified in *L. ochroleuca* can be found in Table 1.

3.2.1.3. *Undaria pinnatifida (Wakame)*.

Undaria pinnatifida or Wakame is a type of brown seaweed that normally grows in the seas of Japan, Korea and New Zealand, but is also commonly found along Western European coasts as an invasive species [48]. Its structure can be divided into the blade (lamina), midrib, sporophyll and root-like formations (haptera) [49]. Wakame is one of the most important global economic marine algae and has a long-standing tradition as food for human consumption [50].

López-Pérez et al. [22] identified 35 hydrocarbons in *U. pinnatifida*, where 4-ethyldecane, pentadecane and 2-methylnonane were the most abundant. The number of hydrocarbons in the volatile fraction of *U. pinnatifida* found in other studies varied from 10 alkanes in Balbas et al. [13] to two hydrocarbons in Ferraces-Casais et al. [11], however differences are likely related to the choice of extraction/concentration methods and operating conditions. Hexadecane and heptadecane [13] and butane [11] were the most abundant hydrocarbons.

López-Pérez et al. [22] also found 34 ketones; with (Z,E)-3,5-octadien-2-one, and 2-propanone and 2-butanone as predominant ones among linear unsaturated and linear saturated ketones, respectively. Balbas et al. [13] identified eight volatile ketones in *U. pinnatifida*, with both (E,E)-3,5-octadien-2-one and β-ionone the most abundant ones, whereas Ferraces-Casais et al. [11] only identified 1-penten-3-one.

Benzaldehyde was the major aromatic aldehyde, 2-hexenal the major linear unsaturated aldehyde and hexanal was by far the major linear saturated aldehyde [22]. Thirteen [13] and seven [11] aldehydes were observed in dried *U. pinnatifida*. Hexanal and 2-heptenal were the most abundant aldehydes found by Balbas et al. [13], while hexanal was the most abundant one in the study by Ferraces-Casais et al. [11].

López-Pérez et al. [22] identified 22 alcohols, the most abundant branched-chain alcohol was 1-(2-methoxypropoxy)-2-propanol, while 1-octen-3-ol and 1-penten-3-ol predominated among linear unsaturated alcohols. There was also a high concentration of (Z)-1,5-octadien-3-ol. Ferraces-Casais et al. [11] reported nine alcohols while Balbas et al. [13] only identified three. The main alcohols were 1-penten-3-ol [11] and 3-decanol [13].

U. pinnatifida also contained six halogenated compounds and seven carboxylic acids in the López-Pérez et al. [22] study, with ethanoic (acetic) acid the most plentiful. *U. pinnatifida* also had an 1-iodo-pentane as the only halogenated compound [11]. Only Balbas et al. [13] perceived carboxylic acids, 2-methylpentanoic and 9-hexadecenoic acids in *U. pinnatifida*.

1,2-Benzenedicarboxylic acid diethyl ester appeared in greater amounts in all seaweed samples than *U. pinnatifida*, while lactic acid ethyl ester and 1,2,3-propanetriol triethanoate were only identified in *U. pinnatifida* [22]. Ferraces-Casais et al. [11] found two esters in *U. pinnatifida*, with the most abundant dibutyl ester of pentanedioic acid, while Balbas et al. 2015 [13] found five, with hexanedioic acid, bis(2-methylpropyl) as the predominant ester.

López-Pérez et al. [22] identified four furans, with the greatest concentration of 2-ethyl-furan and 2-pentyl-furan. The volatile fraction of *U. pinnatifida* in other studies also included 2-ethyl-furan [11,13].

A low abundance of sulfur compounds was evident in *U. pinnatifida*.

The two sulfur compounds identified were dimethyl sulfide and dimethyl sulfoxide [22]. One pyrazine, 2,6-dimethylpyrazine; and one pyridine, 2-ethylpyridine were also detected [22]. Two other volatile compounds were also detected; 2,7-epoxy-megastigma-4,8-diene and 1-methoxy-4-(1′-methylethyl)cyclohexa-1,4-diene [22]. 1,2-Benzisothiazole, 1,3-cyclopentadiene, 5,5-dimethyl-2-ethyl- and 2,5-dimethylhexane-2,5- were also detected by Balbas et al. [13] in *U. pinnatifida*. A summary of the volatile compounds identified in *U. pinnatifida* can be found in Table 1.

3.2.2. Red seaweeds species

3.2.2.1. Palmaria palmata (Dulse). *Palmaria palmata* (*Rhodymenia palmata*) is a red alga (Rhodophyta) in the family Palmariaceae. It grows on the northern coasts of Pacific and Atlantic oceans. It is commonly known as 'dulse' [55], and it has recently become popular as a foodstuff [56]. In Ireland especially and many parts of the British Isles, *P. palmata* is widely available and has a strong historical tradition as component of the local diet [57].

López-Pérez et al. [22] identified 31 hydrocarbons in *P. palmata*. Heptadecane was the most abundant linear saturated hydrocarbon and 3-methylundecane the second most abundant hydrocarbon. Le Pape et al. [41] identified four hydrocarbons, with 3-ethylidene-1-methylcyclopentene as the most abundant one.

Thirty two ketones were identified of which 2-propanone (acetone) and 2-butanone were the most abundant [22], while Le Pape et al. [41] identified only two ketones (2,3-pentanedione and 3-octanone).

P. palmata had the highest concentration of aldehydes in the study by Lopez-Perez et al. [22], with 28 aldehydes identified. Propanal was the major linear saturated aldehyde and (E)-2-pentenal the major linear unsaturated aldehyde and benzaldehyde the major aromatic aldehyde. Le Pape et al. [41] identified seven aldehydes with octanal and nonanal as the most predominant.

There was also a high concentration of volatile alcohols, corresponding to 20 different compounds [14]. The most abundant branched-chain alcohol was 1-(2- methoxypropoxy)-2-propanol, while 1-octen-3-ol and 1-penten-3-ol predominated among linear unsaturated alcohols and 1-pentanol among linear saturated alcohols [22]. Le Pape et al. [41] identified three alcohols (1-butanol, 1-penten-3-ol and 3-methylbutanol) in *P. palmata*.

P. palmata also contained three halogenated compounds, the most abundant was 1-iodopentane; six carboxylic acids, withethanoic (acetic) acid the most abundant and one ester (1,2-benzenedicarboxylic acid diethyl ester). *P. palmata* also contained high abundances of dimethyl sulfide and dimethyl sulfoxide and two pyrazines, 2,6-dimethylpyrazine and 2,3,5,6-tetramethylpyrazine were also identified. In dried *P. palmata* samples, other pyrazines; 2,5-diethylpyrazine and 3-ethyl-2,5-dimethylpyrazine were also reported [58]. The only pyridine and amine detected by López-Pérez et al. [22] were 2-ethylpyridine and dimethylmethanamine, respectively, and were the most abundant in *P. palmata* in comparison to the other aldehydes. Le Pape et al. [41] identified seven halogenated compounds, the most abundant were iodoethane, tribromomethane and chlorobenzene. Neither carboxylic acids nor esters, furans, sulfur compounds, pyrazines or any other volatile compounds were detected by Le Pape et al. [41] in *P. palmata* samples, but this could be due to the DHE extraction/concentration methodology used.

The volatile compounds identified in *P. palmata* can be found in Table 1.

3.2.2.2. Porphyra umbilicalis (Nori). *Porphyra umbilicalis* (commonly known as Nori) is a macrophytic red alga –Rhodophyta- that belongs to an ancient group of red algae, the Bangiophyceae. It is important ecologically and economically [59] and is harvested for human food, and thrives in the harsh conditions of the upper intertidal zone [60].

López-Pérez et al. [22] detected 32 hydrocarbons in *P. umbilicalis* which was the lowest number detected in the seven seaweeds evaluated, four of them were unidentified branched-chain hydrocarbons. The most abundant were 3-methylundecane, 4-methyldecane and 2-methylnonane. These authors identified a considerable number (34) of ketones in *P. umbilicalis*, with (E,E)-3,5-octadien-2-one as the most abundant. Twenty seven aldehydes were also detected, with both hexanal and pentanal as the most abundant. The most abundant alcohols were 1-octen-3-ol and 1,2-dimethylcyclohexanol. No halogenated compounds were detected. The authors identified seven carboxylic acids, with both ethanoic (acetic) and hexanoic acids the most abundant and also one ester (1,2-benzenedicarboxylic acid diethyl ester). These authors identified 4 furans in *P. umbilicalis* with 2-ethyl-furan and 2-pentyl-furan as the most abundant and only 2 pyrazines, 2,6-dimethylpyrazine and 2,3,5,6-tetramethylpyrazine. The volatile compounds identified in *P. umbilicalis* can be found in Table 1.

4. Discussion and future perspectives

Macroalgae are already incorporated as nutritional ingredients into food and drinks, but the search for the ideal macroalgae for a wide range of applications is still on-going. The addition of small amounts of seaweeds or their extracts to food products opens up new prospects for food processing, meat product formulations included. A major difficulty with seaweeds and similar plants is that biological and chemical characteristics may change during growth, in the period from harvest to consumption, and during processing. These changes pose challenges in identifying key character impact volatile(s) that may influence sensory perception in processed foods to which they have been added.

Specific knowledge gaps exist in these chosen macroalgae species regarding, the effect of different harvesting, storage and processing methods of seaweeds on volatile composition; the identification of key volatile compounds that impact sensory perception and the information on the application of seaweeds in processed foods from a sensory perspective.

Regarding storage, the quality of the product is determined by its stability during storage, among other factors (thickness, hardness, color and the absence of foreign materials) [13]. Ideally samples should be extracted and analyzed soon after collection because compounds may change even if frozen (e.g. under nitrogen gas) [61]. However, it is often necessary to store samples for subsequent analysis, due to common setbacks. In any case, analysis of a few representative samples should be made, whenever possible, soon after collection so qualitative and quantitative changes in chemical composition can be detected. When immediate analysis is impossible, samples should be stored in a manner that minimizes changes in metabolite composition. For this purpose, further research [61,62] is required.

Regarding the processing, the nature of many secondary metabolites suggests that some may be labile, necessitating the use of methodologies that do not alter the concentration or structure of compounds [61]. Some authors have studied the influence of processing methods on the volatile compounds of different seaweeds, and depending on the method of their preparation the volatile content may vary greatly [11,42]. However, deeper knowledge on this aspect is also limited and merits further investigation.

It is evident that the production of volatile organic compounds by seaweeds is closely related to the physiology of the species, habitats, maturity [4,63], geographical origin and environmental conditions [22]. Algae are vegetative organisms and must adapt to abiotic stresses (humidity, mineral composition and the sea temperature, light amount and intensity) during their life cycle [44,64]. Therefore, the different compositions and properties of the volatile organic compounds imply different growth conditions of the same species [12].

Furthermore, consumer acceptance of food is closely related to its sensory properties, of which flavor is of prime importance. Some volatile compounds have great impact on the aroma of seaweeds and are considered "character-impact compounds". The diversity of these volatiles compounds present in seaweeds produce different odors like "seafood", "marine", "fish", "licorice", "spices", "fatty", "green" and "honey" [65].

Carboxylic acids are related to odor notes such as spices, honey and licorice, while esters are related to green odor. Notes like fish, marine, fatty and seafood odor are related to presence of amines and pyridines. When present in higher concentrations, compounds contribute to fruity notes in aroma characteristics of some seaweeds [66]. Another class of compounds commonly found in the aroma composition of seaweeds are the ketones, such as β-ionone and 6-methyl-5-hepten-2-one, both potent odorants in seafood. The latter ketone results in compounds having more pleasant odors in seaweed and other foods, such as tomato [65]. Furans are evident in some species of seaweed and are important compounds in the formation of crab flavor, as highlighted by Gu et al. study [36]. Character-impact compounds also include halogenated compounds containing bromine (e.g. dibromoethane, dibromochloromethane, bromodichloromethane and chloroiodomethane) and iodine (e.g. iodoethane, iodopentane) and isoprene (2-methyl-1-3-butadiene), which contribute to the characteristic aroma of the seaweeds, with aromas like marine, crustacean and green [67]; and sweet notes [68], especially in red seaweeds [69].

The aroma diversity of seaweeds is a result of the variety and concentration range of the aroma compounds. Some of these aroma characteristics may be desirable in some applications but unwanted in others. Therefore, further studies to elucidate which edible seaweeds are more suitable in food and feed formulations are necessary. The detailed identification of volatile compounds is very important to elucidate their aroma properties of the final product [19].

5. Conclusion

The production of volatile organic compounds by plants/algae is well known. However, little research has been undertaken on the volatile compounds present in commercially important brown seaweeds (*Himanthalia elongata*, *Laminaria* spp. *Undaria pinnatifida*, and *Laminaria ochroleuca*) or red seaweeds (*Porphyra umbilicalis* and *Palmaria palmata*).

More than 200 different volatile compounds, belonging to 13 or more chemical groups, were present in the six seaweed species reviewed. There was only a limited amount of information available on *Laminaria* spp.

The major volatile compounds found in seaweeds, in decreasing order, were hydrocarbons, ketones, aldehydes, alcohols, halogen or sulfur-containing compounds, acids, esters, furans, and phenols. Volatile compounds reported in previous works depended, mostly, on the extraction methodology and GC–MS conditions. The impact of volatile compounds on sensory perception is dependent upon abundance and odor threshold.

Extended work needs to be done related to the volatile compounds of seaweeds in connection with their sensory characteristics. Further work is aimed at evaluating the aroma characteristics of seaweeds with the objective of evaluating the influence of flavor and odor notes on acceptability of new seaweed-containing products.

CRediT authorship contribution statement

Elena Garicano Vilar:Conceptualization, Writing - original draft, Writing - review & editing.**Maurice G. O'Sullivan**:Supervision, Writing - review & editing.**Joseph P. Kerry**:Supervision, Writing - review & editing.**Kieran N. Kilcawley**:Supervision, Writing - review & editing.

Declaration of competing interest

None.

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