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Phlorotannins from New Zealand brown seaweeds: Extraction, antioxidant activity, and food applications

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ABSTRACT

Brown seaweed, a type of marine macroalgae, is a sustainable resource for human consumption that plays an important role in several cultures, including Aotearoa New Zealand. Brown seaweeds have a relatively high content of phenolic compounds and, exclusively, phlorotannins, which have garnered increasing attention due to their bioactive properties. Applications of these phenolic compounds have been developed for therapy, food additives, material manufacturing, and fertilisers. Among these, their antioxidant property is especially important for the food industry, but limited research has been conducted. This review investigated the nutrition profile of New Zealand brown seaweed species, which are rich in macronutrients, and addressed safety concerns regarding heavy metals and iodine. Phlorotannin content, extraction methods, and their promising antioxidant activities were then compared between New Zealand and global brown seaweeds. According to the current research, they have comparable phlorotannin content and antioxidant activities. More importantly, the potential of applying brown seaweed species as an antioxidant in food matrices was explored. Although successful trials have utilised (New Zealand) brown seaweed extracts as antioxidants for various foods, their widespread commercial use remains rare. The seaweed industry in New Zealand has not been established, and the seaweed is heavily reliant on wild harvest and imports. In conclusion, more effort is needed to develop a comprehensive, evidence-based understanding of New Zealand's brown seaweeds, ultimately enabling the commercialization of this promising resource as antioxidants in food products.

1. Introduction

Seaweeds are marine macroalgae, which have a variety of habitats, ranging from shallow intertidal areas to deeper zones. Seaweed can be categorised into two kingdoms: Chromista (brown seaweeds) and Plantae (red and green seaweeds), which differ in their photosynthetic pigments (Neill et al., 2016). Seaweed aquaculture has grown rapidly since 1990, reaching an annual production volume of 36.4 million tons and a value of 17.9 billion USD in 2022, equivalent to 27.1 % by volume of total aquaculture production. (FAO, 2024; Zion, 2024). The production of macroalgae has been increasing for the past few decades, with a 5.8 % average annual growth rate from 2000 to 2022, driven by consumer demand for plant-based and functional foods, with high-value applications commanding premium prices. (FAO, 2024).

Direct consumption, as human food and biomass for animal feed, is the major utilisation of seaweeds. They are a sustainable resource with a remarkably lower carbon footprint and minimal inputs than terrestrial plants. Edible macroalgae (*Porphyra, Caulerpa, Sargassum*, etc.) play an important role in the diet of East Asian and Pacific countries, such as China, Japan, Indonesia, and Māori (Reboleira et al., 2019), as ingredients in soups, salads, and other cuisines (Subbiah et al., 2023). China, Indonesia, and South Korea are the three major exporters, while China, Japan, and the USA are the leading importers, resulting in a total trading amount worldwide of 1.1 billion USD in the year 2020 (FAO, 2024). 99.3 % of global seaweed aquaculture is produced in Asian countries, while Oceania countries account for only 0.03 % (FAO, 2024). As global demands for sustainable and nutrient-rich foods grow, seaweed stand out as renewable, ocean-based resource with a minimal environmental footprint. From an economic and business viability perspective, seaweeds present significant opportunities, particularly for coastal communities and companies focused on sustainable food systems. The cultivation of seaweeds requires no freshwater, arable land, or

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synthetic fertilisers, resulting in low production costs and a reduced environmental impact compared to traditional agriculture. However, commercial seaweed aquaculture has not been established in New Zealand (NZ), and the seaweed industry is just in its cradle (White & White, 2020). Strict regulation applies to the cultivation of Wakame (Undaria pinnatifida), classified as an exotic species under New Zealand's Biosecurity Act 1993. Commercial returns and demand for downstream seaweed products remain uncertain, contributing to an absent or immature supply chain. Seaweed businesses, therefore, rely heavily on wild harvest or import (Jacob Nepper-Davidsen, 2023). Only *Ulva* spp., *Pyropia* spp., *Undaria pinnatifida, Ecklonia radiata*, and *Macrocystis pyrifera* are the species whose derivative products are sold by a limited number of commercial businesses (White & White, 2020).

Additionally, seaweeds have been used as medicine in ancient China, Japan, Egypt, and India since the Common Era (Polat et al., 2023). They have >54 trace elements required for the human body's physiological functions in quantities greatly exceeding vegetables and other land plants. (Dhargalkar & Perira, 2005). Functional substances in macroalgae, such as ω−3 fatty acids, lectin, acrylic acid, and fucoidan, have attracted much research for their health benefits, as they are almost the secondary metabolites helping seaweeds survive in hostile marine environments. Therefore, seaweeds could be used for antioxidant, antimicrobial, antiviral, anti-inflammatory, and antitumour substances due to their unique bioactive compounds. (Akbari et al., 2022; Cotas et al., 2020; Knížatová et al., 2021; Olsthoorn et al., 2021; Sanjeewa et al., 2016; Subbiah et al., 2023; Wijesinghe & Jeon, 2012). In food additives, agar, alginate, and carrageenan are the most important hydrocolloids extracted from seaweed, employed as stabilisers, thickeners, and gelling agents. Other applications include biofuel, cosmetics, fertilisers, soil conditioners, and pharmaceutical ingredients. (Polat et al., 2023).

Among them, brown macroalgae (*Phaeophyceae*), primarily coloured by fucoxanthin and phlorotannins, are widely used as biofuels, animal feed, and food additives (Hayes, 2015). Due to the fact that they contain more bioactive components than either green or red seaweeds (Prabhasankar et al., 2009), more functionally related applications have been developed. Although more research recently proved its diverse bioactivities and pharmaceutical application (Purcell-Meyerink et al., 2021), little research focuses on the lipid antioxidant activity applied in food products, whether its extraction or as a whole. Antioxidation is the most pertinent property of seaweed for novel scientific research in the food industry.

Lipid oxidation is a challenge in food preservation and product development, threatening nutritional value and shelf life. Through either auto-oxidation, photosensitised oxidation, or enzymatic oxidation, fatty acids in food (especially polyunsaturated fatty acids, PUFA) degenerate and produce radical species, brown-coloured substances, and volatile organic acids (Wang et al., 2023). Off-flavour, rancidity flavour, and a concomitant reduction in shelf life caused by these oxidised compounds significantly affect the product quality, sensory attributes, and nutritional value, and can even cause a series of health issues. Applying antioxidants in foods can reduce the rate of oxidation, where the definition of antioxidants is usually a substance that can delay or inhibit oxidation reactions at low concentrations. (Franco et al., 2019). Antioxidants can be classified into two types according to their origin: synthetic and nature-sourced. The advantages of synthetic antioxidants include high efficacy and stability in thermal processing, as well as economic efficiency. Tert-butyl hydroquinone (TBHQ, E319), butylated hydroxyanisole (BHA, E320), butylated hydroxytoluene (BHT, E321), and 4-hexylresorcinol (E586) are representatives of synthetic antioxidants effectively used in lipid-rich foods. However, the health risks and toxicity concerns restrict their application in foods. Some synthetic antioxidants are even considered carcinogenic. Natural antioxidants, such as tocopherols (E306– E309) and rosemary extract (E392), on the other hand, are being investigated for safety considerations. This class of antioxidants usually has a phenol-like structure with multiple phenolic hydroxyl groups or aliphatic substituents, which are the active centres for oxidation resistance. Considering the high content of polyphenols in brown seaweeds, they have a huge potential to be used as novel natural antioxidants.

This review focuses on the present-day and future potential applications of brown seaweed species, especially for those in New Zealand. The unique bioactive compounds found in brown seaweed, phlorotannins, are discussed, considering their concentration, antioxidant mechanisms, and extraction methods. The antioxidant activity of brown seaweed is primarily attributed to these compounds, which constitute a significant fraction of its polyphenols. The antioxidant potential is positively correlated with the concentration of these compounds (Zhang et al., 2018). Applications of brown seaweeds and phlorotannins are further explored in pharmaceutical and food contexts, owing to their bioactive properties, including anti-inflammatory, antimicrobial, and radioprotective activities. While this review focuses on antioxidant activity, these additional biological effects reinforce the broader functional potential of phlorotannins in food and therapeutic contexts. Applications of brown seaweeds and phlorotannins were further explored regarding, pharmacy, food additives, livestock feed, and fertilisers, thanks to their outstanding properties such as anti-inflammatory, antimicrobial and radioprotective. Finally, the potential of using brown seaweed in food as an antioxidant was assessed, and suggestions were given for the New Zealand seaweed industry.

2. New zealand brown seaweed

2.1. Species

Brown macroalgae are ubiquitous on most of New Zealand's shorelines. Local Māori have used seaweeds for hundreds of years as food and crafting materials. (Wheeler Thomas et al., 2021). Nowadays, some are commercial species, marketed as 'kelp' (Smith et al., 2010), including edible wakame (*Undaria pinnatifida*) (Neill et al., 2016) and those producing alginates (*Laminaria brasilliensis, Ecklonia cava, Macrocystis pyrifera*, etc.) (Abdullah et al., 2021). At least 146 species of brown seaweed can be found in New Zealand, and the *Ecklonia radiata* is the most widely spread species, accounting for >25 % of the total. (Jacob Nepper-Davidsen, 2023). The most common species have been listed in Table 1 (Neill et al., 2016).

2.2. Nutrition components

In general, seaweeds contain rich macronutrients: protein, insoluble fibre, and soluble carbohydrates, and are also high in minerals and vitamins (Ozogul et al., 2024). Moisture content of seaweeds can be as high as 150 %– 1560 % dry weight (dw) (Marsham et al., 2007). According to the proximate analyses, Ochrophyta (brown seaweeds) have the highest mean insoluble fibre content and lipid content compared to the other two phyla of seaweeds (*Chlorophyta*, green seaweeds, and Rhodophyta, red seaweeds), while the lowest content is in ash, soluble, and protein Hrstich (2021). The mean insoluble fibre content for brown seaweeds is 19.98 % dw and is highly variable from species to species. This value for *Durvillaea antarctica*, for instance, is almost 44 % dw; meanwhile, it is quite low for *U. pinnatifida,* namely 16.26 % dw (Rupérez & Saura-Calixto, 2001). Although the lipid contents of most macroalgae species are no >5 % dw, the mean lipid content for brown seaweeds reaches up to 4.60 %. Soluble carbohydrates for brown seaweeds range between 55 %– 70 % dw (Rajapakse & Kim, 2011), which may include alginates, alginic acid, carrageenan, fucoidan, and sargassan (Hrstich, 2021). Protein content in Ochrophyta is the least among the three phyla, at an average of 9.20 % Battershill, 2024). *U. pinnatifida*, interestingly, with the lowest insoluble fibre content, has a relatively high protein content ranging between 11 %– 24 % dw. Considering the high fibre content, seaweeds can therefore be a good source of dietary fibre, and a potential prebiotic (Polat et al., 2023).

Macronutrients have a wide distribution within each phylum, and

Table 1
Brown Seaweed species in New Zealand and their characteristics.

Order	Family	Species	Habitat	Morphology	Depth range (m)	Characteristic(s)
Dictyotales	Dictyotaceae	*Dictyota kunthii*	Southern hemisphere	Strap / shrub-like	0–20	Widespread in NZ; fleshy tongues, divided blades
Laminariales	Alariaceae	*Undaria pinnatifida*	Globally	Bladed	0–20	Large blades (Wakame)
	Laminariaceae	*Macrocystis pyrifera*	South Island mainly	Bladed / shrub-like	1–40	Can be 20 m high.
	Lessoniaceae	*Ecklonia radiata*	Globally	Bladed	1–100	large blade; can habit deeply
		Lessonia tholiformis	Chatham Islands	Strap / shrub-like	1–15	**Native**; long, smooth blade
		Lessonia variegata	North & South Island	Strap / shrub-like	0–20	**Native**; widely spaced marginal teeth blades
Desmarestiales	Desmarestiaceae	*Desmarestia ligulata*	South Island mainly	Shrub-like	1–40	Feather-like blades
Scytothamnales	Splachnidiaceae	*Splachnidium rugosum*	Southern hemisphere	Bladders / shrub-like	0–1	swollen stems and side branches
	Scytothamnaceae	*Scytothamnus australis*	Southern hemisphere	Shrub-like	0–1	bushy/scruffy appearance
Fucales	Durvillaeaceae	*Durvillaea antarctica*	Southern hemisphere	Bladed / strap-like	0–2	Leathery-like surface; Widespread on the NZ coast rocks
		Durvillaea chathamensis	Chatham Islands	Bladed / strap-like	0–5	**Native**; Leathery-like surface; Can be 15 m long.
		Durvillaea poha	Southern South Island	Bladed / strap-like	0–2	**Native**; Leathery-like surface; In danger
		Durvillaea willana	South Island mainly	Bladed, shrub/strap-like	0–1	**Native**; Leathery-like surface
	Hormosiraceae	*Hormosira banksii*	NZ & Australia	Bladders / shrub-like	0–5	**Native**; widespread in NZ
Order	Family	Species	Habitat	Morphology	Depth range (m)	Characteristic
Fucales	Sargassaceae	*Carpophyllum angustifolium*	Northern North Island	Shrub-like	0–20	**Native**; egg-shaped air bubbles
		Carpophyllum flexuosum	North & South Island	Shrub-like	0–45	**Native**; widespread in NZ
		Carpophyllum maschalocarpum	North & South Island	Shrub-like	0–45	**Native**; widespread in NZ
		Carpophyllum plumosum	Northern North Island	Shrub-like	0–45	**Native;** stalked and rounded air bladders
		Cystophora platylobium	Northern North Island	Shrub-like	0–10	**Native**; slightly oval air bladders
		Cystophora retroflexa	NZ & Australia	Shrub-like	0–15	**Native**; oval air bladders
		Cystophora scalaris	South Island mainly	Shrub-like	0–15	**Native**; oval to round air bladders
		Cystophora torulosa	NZ & Australia	Shrub-like	0–10	**Native**; swollen branchlets; round air bubbles
		Landsburgia quercifolia	Almost all deep water	Shrub-like	0–40	**Native**; small oakleaf-shaped leaves
		Phyllotricha verruculosa	Southern South Island	Shrub-like	1–40	**Native** (introduced); in danger
		Sargassum scabridum	Northern North Island	Shrub-like	0–10	**Native**; small air bubbles
		Sargassum sinclairii	Widespread in NZ	Shrub-like	1–40	**Native**; toothed margin leaf-like blades
Order	Family	Species	Habitat	Morphology	Depth range (m)	Characteristic
Fucales	Xiphophoraceae	*Xiphophora chondrophylla*	Northern North Island	Strap / shrub-like	0–5	**Native**; narrower and more forked blades towards the tip
		Xiphophora gladiata	South Island mainly	Strap / shrub-like	0–25	**Native**; fan-shaped as a whole
	Seirococcaceae	*Marginariella boryana*	South Island mainly	Strap / shrub-like	1–40	**Native**; toothed edges, long blades
		Marginariella urvilliana	South Island mainly	Strap / shrub-like	1–40	**Native**; large air bubbles

a: The depth range of the specific species is only considered in New Zealand.

the same species have different nutritional components. There is a lack of consistent inter-phylum variation; however, insoluble fibre contents demonstrated a more dispersed distribution. (Hrstich, 2021). The nutritional chemistry of seaweeds, at the same time, is substantially affected by environmental conditions and maturity, including sunlight exposure, sea wave exposure, water temperature, salinity, and nutrient availability. Nonetheless, for a large proportion of seaweed species, the nutritional values remain poorly described. (Britton et al., 2021).

New Zealand brown seaweeds have parallel nutritional components compared to global species, although the data may be incomparable due to the inconsistent sample collecting and analysis methods. They still have a higher lipid content, averaging at 1.49 % (Hrstich, 2021). Similarly, their mean protein content is relatively lower than that of green and red seaweeds. (Battershill, 2022). Only a few species, such as *Ecklonia radiata, Hormosira banksia, Macrocystis pyrifera, Undaria pinnatifida*, and *Durvillaea antarctica*, have been reported on their nutritional components. (Battershill, 2022; Hrstich, 2021; Smith et al., 2010; Subbiah et al., 2023).

Minerals, including iron, calcium, sodium, potassium, as well as vitamins (A, B, C, and E), can be found in all classes of seaweeds (Battershill, 2024; Da Silva et al., 2025; Hrstich, 2021; Ilyas et al., 2023; Skrzypczyk et al., 2024; Subbiah et al., 2023). In light of bioaccumulation, seaweeds may contain high concentrations of heavy metals (arsenic, mercury, and lead), which may cause concerns about the safety of consumption. Considering the more toxic inorganic arsenic in food, the maximum limitation of inorganic arsenic detected in seaweed is 6.7 mg/kg dw (FSANZ, 2022). The total arsenic in unprocessed *E. radiata* is 36 mg/kg dw with 1.5 mg/kg inorganic arsenic (Peter et al., 2023; Smith et al., 2010). In Europe, seaweeds used as food ingredients are regulated by Commission Regulation (EU) No 420/2011 for cadmium (< 0.33 mg/kg dw) and lead contamination (< 0.67 mg/kg dw) (Regulation 420/2011, 2011). The heavy metal contents of wild-collected NZ seaweeds are below the maximum threshold. Notably, the iodine contents in brown seaweeds are usually extremely high (Table 2), which may cause thyroid dysfunction (Skrzypczyk et al., 2024). The recommended dietary allowance (RDI) of iodine is 150 μg/day for adults, and the tolerable upper intake level (UL) is 1100 μg/day for adults (NHMRC, 2006). Therefore, Food Standards Australia New Zealand (FSANZ) advises that one serve per week of brown seaweed is the cap for pregnant and breastfeeding women and children (FSANZ, 2016; Smith et al., 2010). Similarly, high quantities of Cr, Mg, and Fe may also limit the consumption amount of brown seaweeds (Battershill, 2022; Skrzypczyk et al., 2024). Fortunately, the seaweed processing for bioactive ingredient extraction or consumption can effectively reduce the heavy metals and iodine content, such as cleaning, blanching, drying, and rehydration (Cecilie Bay Wirenfeldt, 2023; Van Tuinen et al., 2023). Altogether, under the unpolluted natural or aquaculture farming environments and appropriately processed, it is safe to consume seaweeds directly or as an additive (Smith et al., 2010).

3. Antioxidant activity

3.1. Phenolic compounds

According to the evolutionary biology theory, marine macroalgae produce unique bioactive substances that allow them to defend against fluctuations in external environmental factors and biological stressors (Reboleira et al., 2019). Phenolic and polyphenolic acids, bromophenols, flavonoids, and carotenoid pigments are the main secondary metabolites considered as bioactive compounds (Cotas et al., 2020).

Brown Seaweeds contain a unique polyphenolic acid called phlorotannins, a subclass of tannins, as both primary and secondary metabolites (Sónia et al., 2019). Synthesizing and accumulating phlorotannins is a critical photoprotective strategy for aquatic macroalgae. Inside seaweed cells, phlorotannins mainly play the role of anti-herbivory defence (appetite suppressant), antifouling, ultraviolet light absorber, and antioxidant (Ford et al., 2019). The outstanding bioactivity properties of phlorotannins have attracted research in anti-diabetic, anti-bacterial, radioprotective, anti-cancer, anti-proliferative, matrix metalloproteinase inhibitory, hyaluronidase inhibitory, anti-inflammatory, anti-allergic, antioxidant, and even hair growth activities (Besednova et al., 2019; Chakraborty et al., 2017; Cotas et al., 2020; Sanjeewa et al., 2016; Shibata et al., 2008). In other words, phlorotannins are the key phenolic compounds in *Phaeophyceae* for antioxidant activity (Cotas et al., 2020), whose activity can be 2– 10 fold higher than that of ascorbic acid or Vitamin E (Shibata et al., 2008).

Phlorotannin is a phloroglucinol (1,3,5-trihydroxybenzene) oligomer whose molecular weight ranges between 0.1 and 100 kDa, reaching up to 16 units (Corsetto et al., 2020). According to the interphloroglucinol linkage type, they can be classified into six categories. Fuhalols only have an aliphatic bond between phloroglucinols; fucophlorethol and phlorethol use ether linkage for monomers; fucophlorethols contain combinations of C—C bond and ether bond; and eckols and carmalols are based on dibenzodioxin linkage, where eckols have more than one phenoxyl group substitute dibenzodioxin three-ring at C-4 (Meng et al., 2021). Due to the structural differences and varying oxidation modes, they exhibit different antioxidant activities across categories (Shibata et al., 2008). The polymerisation of phloroglucinol does not affect the antioxidant capacity, and instead, the number of free or available phenolic hydroxyl groups and the resonance stabilisation of radical species are the determinants (Heffernan et al., 2015; Hermund et al., 2018; Zhang et al., 2018).

In general, phlorotannin content in brown seaweeds varies between 0.5 % and 20 % dw (Ford et al., 2019). Table 3 compared the phlorotannin contents from New Zealand brown seaweed species to those from the global. Regardless of the extraction techniques used, New Zealand species show a similar range of phlorotannin concentration. The comparison is, however, limited due to the lack of research, particularly for New Zealand species (McCarthy et al., 2024). Jacob Nepper-Davidsen (2023) Suggested that New Zealand native *E. radiata* has a significantly greater amount of phlorotannins compared to commercially grown species in the northern hemisphere. More research focuses on the construction of a New Zealand brown seaweed biomass database, which is suggested for systematic study and comparison.

The phlorotannin content in brown seaweed spans a broad spectrum and is affected by various factors. The most well-known factor is the geographical difference, which can be further explained by the intensity and length of sunlight exposure (McKinney et al., 2025), seawater temperature, and environmental nutrition (Pavia & Toth, 2000). The higher global solar radiation in summer and thus seawater temperature explained why most species accumulate the highest phlorotannin levels this season (Kamiya et al., 2010). *Sargassum confusum*, in contrast, has the opposite trend, with its peak phlorotannin content occurring in winter (Table 3). This may be attributed to other environmental variables or stress, such as overwhelming solar radiation and seawater temperature, or the presence of epiphytes or herbivory (Pavia & Toth,

Table 2
Proximate analyses and iodine content for several brown seaweed species.

Species	Protein[a]	Lipids[a]	Total Carbohydrates[a]	Total Fibre[a]	Ash[a]	Iodine (μg/g)
Carpophyllum maschalocarpum[b]	3.9 %	1.3 %	64.5 %	6.7 %	23.7 %	N.A.[c]
Cystophora retroflexa[b]	5 %	2.45 %	63.7 %	2.71 %	27 %	N.A.
Ecklonia radiata[b]	7.02 %	1.25 %	49 %	5 %	38 %	179.0
Fucus vesiculosus	6.4 %	2.1 %	14.9 %	46.7 %	N.A.	405
Himanthalia elongata	5.4 %	1.5 %	30.8 %	37.14 %	N.A.	96.0
Macrocystis pyrifera[b]	8.8 %	1.3 %	55.6 %	45.4 %	34.4 %	212.5
Saccharina latissima	6.29 %	1.06 %	69.79 %	N.A.	9.55 %	4605
Sargassum sinclairii[b]	6.96 %	1.87 %	53 %	4.8 %	36 %	N.A.
Undaria pinnatifida[b]	9.4 %	4.8 %	54.5 %	48.2 %	31.5 %	17.41
Xiphophora chondrophylla[b]	6.96 %	1.0 %	52 %	22.0 %	19.8 %	N.A.
Zonaria turneriana[b]	6.8 %	1.2 %	58 %	19.6 %	25.1 %	N.A.

[a] : Data were presented in dry weight if not specified.
[b] : NZ-sourced brown seaweeds.
[c] : data not available.

Table 3
Phlorotannin content comparison between New Zealand brown seaweed species and worldwide.

Species	Origin	Extraction condition	Phlorotannin Content	Reference
Carpophyllum flexuosum	New Zealand	MAE. 160 °C, 3 min then oven-dried 60 °C, 48 h	158 ± 3 μg PGE/mg dw [b]	(Zhang et al., 2018)
Carpophyllum plumosum	New Zealand	MAE. 160 °C, 3 min then oven-dried 60 °C, 48 h	92 ± 6 μg PGE/mg dw	(Zhang et al., 2018)
Cystophora retroflexa (summer)[a]	New Zealand	SLE. 60 % acetone, 1 h	252.63 ± 5.71 μmol GAE/g dw [c]	(McCarthy et al., 2024)
Cystophora torulosa (spring) [a]	New Zealand	SLE. 60 % acetone, 1 h	127.05 ± 6.29 μmol GAE/g dw	(McCarthy et al., 2024)
Desmarestia ligulate (spring)[a]	New Zealand	SLE. 60 % acetone, 1 h	16.26 ± 5.69 μmol GAE/g dw	(McCarthy et al., 2024)
Durvillaea spp. (spring) [a]	New Zealand	SLE. 60 % acetone, 1 h	41.50 ± 3.29 μmol GAE/g dw	(McCarthy et al., 2024)
Ecklonia radiata	New Zealand	SLE. 50 % MeOH (pH 2), 25 °C, 1 h + 70 % acetone, 25 °C, 1 h	3.6 %– 12.4 % dw	(Jacob Nepper-Davidsen, 2023)
Hormosira banksia (winter) [a]	New Zealand	SLE. 60 % acetone, 1 h	35.12 ± 4.48 μmol GAE/g dw	(McCarthy et al., 2024)
Lessonia variegata (spring) [a]	New Zealand	SLE. 60 % acetone, 1 h	12.52 ± 5.61 μmol GAE/g dw	(McCarthy et al., 2024)
Macrocystis pyrifera (spring) [a]	New Zealand	SLE. 60 % acetone, 1 h	27.67 ± 4.53 μmol GAE/g dw	(McCarthy et al., 2024)
Marginariella boryana (spring) [a]	New Zealand	SLE. 60 % acetone, 1 h	98.57 ± 11.62 μmol GAE/g dw	(McCarthy et al., 2024)
Marginariella urvilliana (spring) [a]	New Zealand	SLE. 60 % acetone, 1 h	47.29 ± 5.80 μmol GAE/g dw	(McCarthy et al., 2024)
Undaria pinnatifida	New Zealand	SFE. Water, 30 bar, 210 °C, 0.33 h	990 ± 4 μg PGE/ g dw	(Gan & Baroutian, 2022)
Undaria pinnatifida (summer) [a]	New Zealand	SLE. 60 % acetone, 1 h	15.36 ± 2.10 μmol GAE/g dw	(McCarthy et al., 2024)
Sargassum sinclairii (Spring)[a]	New Zealand	SLE. 60 % acetone, 1 h	140.77 ± 20.82 μmol GAE/g dw	(McCarthy et al., 2024)
Xiphophora gladiata	New Zealand	SLE. 60 % acetone, 1 h	79.46 ± 12.24 μmol GAE/g dw	(McCarthy et al., 2024)
Species	Origin	Extraction condition	Phlorotannin Content	Reference
Ascophyllum nodosum	Sweden	SLE. 60 % acetone, 4 °C, 24 h, dark	4.32 % dw	(Pavia & Toth, 2000)
Chaetopteris plumosa	Russia	SLE. 70 % acetone, 1 h, twice	2.4 % dw	(Lemesheva et al., 2023)
Cystoseira nodicaulis	Ireland	Dialysis. 80 % EtOH, 25 °C, 24 h + < 3k MWCO [b]	89.14 ± 2.57 μg PGE/mg	(Heffernan et al., 2015)
Dictyosiphon foeniculaceus	Russia	SLE. 70 % acetone, 1 h, twice	7.2 % dw	(Lemesheva et al., 2023)
Ecklonia radiata	Australia	MAE. 160 °C, 3 min + oven-dried 60 °C, 48 h	20 ± 1 PGE μg PGE/mg dw	(Zhang et al., 2018)
Ectocarpus siliculosus	Russia	SLE. 70 % acetone, 1 h, twice	4.8 % dw	(Lemesheva et al., 2023)
Fucus serratus	Ireland	Dialysis. 80 % EtOH, 25 °C24 h + <3k MWCO	180.55 ± 16.98 μg PGE/mg	(Heffernan et al., 2015)
Fucus vesiculosus	Ireland	Dialysis. 80 % EtOH, 25 °C, 24 h + <3k MWCO	231.95 ± 8.97 μg PGE/mg	(Heffernan et al., 2015)
Fucus vesiculosus	Ireland	UAE. 35 kHz, 50 % EtOH, 30 min	476.3 ± 2.2 μg PGE/mg	(Ummat et al., 2020)
Fucus vesiculosus	Sweden	SLE. 60 % acetone, 24 h, 4 °C, dark	4.88 % dw	(Pavia & Toth, 2000)
Fucus vesiculosus	Russia	SLE. 70 % acetone, 1 h, twice	16.2 % dw	(Lemesheva et al., 2023)
Himanthalia elongata	Ireland	Dialysis. 80 % EtOH, 25 °C, 24 h + <3k MWCO	130.89 ± 0.45 μg PGE/mg	(Heffernan et al., 2015)
Laminaria digitata	France	PLE. 80 % methanol, 40 °C, 3 h	0.2 ± 0.1 % dw	(Connan et al., 2006)
Laminaria hyperborea	France	PLE. 80 % methanol, 40 °C, 3 h	2.6 ± 1.5 % dw	(Connan et al., 2006)
Macrocystis pyrifera	Chile	EAE. Alginatelyase, fucoidanase, glucanase 25 °C, 36 h	2.14 % ± 0.25 % wt	(Leyton et al., 2017)
Myagropsis myagroides (winter) [a]	Japan	SLE. 80 % methanol, 24 –72 h	≈ 3.2 % dw	(Kamiya et al., 2010)
Saccharina latissima	Spain	PLE. 10 MPa, 80 °C water	2.53 ± 0.15 μg PGE/mg dw	(Da Silva et al., 2025)
Sargassum angustifolium	Iran	UAE. 400 W (100 %) 70 % ethanol, 40 min	3.40 ± 1.00 μg PGE/mg dw	(Hodhodi et al., 2022)
Sargassum confusum (winter) [a]	Japan	SLE. 80 % methanol, 4 °C, 24 –72 h	≈ 12.7 % dw	(Kamiya et al., 2010)
Sargassum fusiforme	China	SLE. 30 % ethanol, 25 °C, 0.5 h	63.61 ± 0.16 μg PGE/mg dw	(Li et al., 2017)
Species	Origin	Extraction condition	Phlorotannin Content	Reference
Sargassum ilicifolium	Sri Lanka	SLE. 30 % ethanol, 30–40 °C, 6 h	355 ± 4 μg PGE/mg dw	(Kaushalya & Gunathilake, 2022)
Sargassum muticum	France	PLE. 80 % methanol, 40 °C, 3 h	4.9 ± 2.9 % dw	(Connan et al., 2006)
Sargassum hemiphyllum (Spring and summer) [a]	Japan	SLE. 80 % methanol, 4 °C, 24 –72 h	≈ 14.2 % dw	(Kamiya et al., 2010)
Sargassum patens (summer) [a]	Japan	SLE. 80 % methanol, 4 °C, 24 –72 h	≈ 6.5 % dw	(Kamiya et al., 2010)
Sargassum schroederi	Brazil	SLE. 70 % acetone, 2 h	4.30 ± 0.78 % dw	(Ank et al., 2019)
Sargassum siliquastrum (summer) [a]	Japan	SLE. 80 % methanol, 4 °C 24 –72 h	≈ 9.5 % dw	(Kamiya et al., 2010)
Sargassum zonale	Brazil	SLE. 70 % acetone, 2 h	1.72 ± 0.49 % dw	(Ank et al., 2019)
Undaria pinnatifida	China	HTE. 52 % ethanol, 170 °C, 5.2 h	10.7 ± 0.2 mg GAE/g dw	(Dong et al., 2019)

[a] : Seasonal variations were reported. The highest phlorotannin content was recorded.
[b] : phloroglucinol equivalents;.
[c] : GAE: Gallic Acid Equivalent
Pressurized liquid (PLE), ultrasound-assisted (UAE), high temperature (HTE), microwave-assisted (MAE), and supercritical fluid (SFE) extraction
a: Seasonal variations were reported by the author. The highest phlorotannin content was recorded.
b: Molecular weight cut-off

Pressurized liquid (PLE), ultrasound-assisted (UAE), high temperature (HTE), microwave-assisted (MAE), and supercritical fluid (SFE) extraction
a: Seasonal variations were reported by the author. The highest phlorotannin content was recorded.
Pressurized liquid (PLE), ultrasound-assisted (UAE), high temperature (HTE), microwave-assisted (MAE), and supercritical fluid (SFE) extraction.

2000). Sea wave exposure, a factor that has received less attention, has been proven to affect *U. pinnatifida* phlorotannin content, which had the highest value in spring (McCarthy et al., 2024). Likewise, Ank et al. (2019) figured out that the variations of phlorotannin content among 17 Brazilian brown seaweed species were greater at higher latitudes, where the seawater is colder than that closer to the equator. For instance, *Canistrocarpus cervicornis* collected from 22°S presented higher phlorotannin content compared to those from 8°S, while it's not the case for *Dictyota mertensii* from the same origins. Even within the same seaweed thallus, inconsistent phlorotannin contents can be observed, known as the "intra-thallus variation" (Connan et al., 2006). The variation pattern differs across species. Connan et al. argued that the theory of utilising phlorotannin compounds protects from herbivore and grazing, and thus they accumulate primarily in the most valuable tissues (e.g., reproductive and meristematic tissues). They also considered the interaction between seaweed and its marine environment.

It's worth noting that the phlorotannin content detected in brown seaweeds is influenced by the extraction conditions and techniques used. The conventional technique is solid-liquid extraction (SLE), using a large volume of (aqueous) organic solvent as extractants, e.g., ethanol (aq.), methanol (aq.), acetone (aq.). A typical condition involves the liquid-to-solid (solvent to dry seaweed powder) ratio at 5– 50 mL/g, with an extracted time of 1– 24 h at the target temperature (Table 3). Organic solvents interrupt the intermolecular hydrogen bonds and hydrophobic interactions. However, higher concentration can increase the polarity of extracted phlorotannin, leading to worse yield, solubility, and bioactivity (Najibi et al., 2025). Further purification could be performed by other organic solvents that differ from the one used for crude extraction (Kaushalya & Gunathilake, 2022). Advanced extraction techniques, such as pressurized liquid (PLE) (Da Silva et al., 2025), ultrasound-assisted (UAE) (Hodhodi et al., 2022), high temperature (HTE) (Dong et al., 2019), microwave-assisted (MAE) (Da Silva et al., 2025; Zhang et al., 2018), and supercritical fluid (SFE) extraction, that use external physical assistance to more easily break down cell structures and release polyphenol compounds are considered to improve extraction efficiency (Gan & Baroutian, 2022). Additionally, biological methods are also used for increasing the extraction yield. Enzyme-assisted extraction (EAE) is a green technique that produces less waste and requires less energy (Zheng et al., 2022). The detailed extraction methods and parameters used, therefore, should be taken into account when comparing the phlorotannin contents.

Regarding the phlorotannin content difference among species, it is difficult to draw a direct conclusion. Lemesheva et al. (2023) Compared five phaeophyceae orders under the same extraction and concluded that Fucales has the highest phlorotannin content. *F. serratus, F. vesiculosus, S. hemiphyllum, S. sinclairii, and C. retroflexa* had relatively high concentrations. Along with Fucales, *U. pinnatifida* also presents a surprisingly abundant amount of phlorotannins (Gan & Baroutian, 2022).

Other phenolic compounds, including bromophenols, flavonoids, and phenolic terpenoids, also have antioxidant activity, but fewer studies have focused on these compounds of seaweeds (Chakraborty et al., 2017; Reboleira et al., 2019; Sanjeewa et al., 2016).

3.2. Mechanism of action

It is less likely to overestimate the importance of the antioxidant components in the food matrices, especially those rich in lipids. Oxidation, in most cases, causes the loss of nutrients, sensory attributes, and product quality, and even leads to health problems (Srinivasan & Kirk, 2017). Phlorotannins, as a type of polyphenol (PP) in brown seaweeds, can repel the oxidation reaction for unsaturated fatty acids. The mechanisms of antioxidant activity of PP are shown in Fig. 1. The oxidation effect of lipoxygenase is not discussed here, as there is less evidence that PP inhibits its activity. The polyphenolic compounds can quench active oxygen species ($^1O_2$), chelate catalyst metal ions, and act as hydrogen donors and radical scavengers (Maqsood et al., 2014;

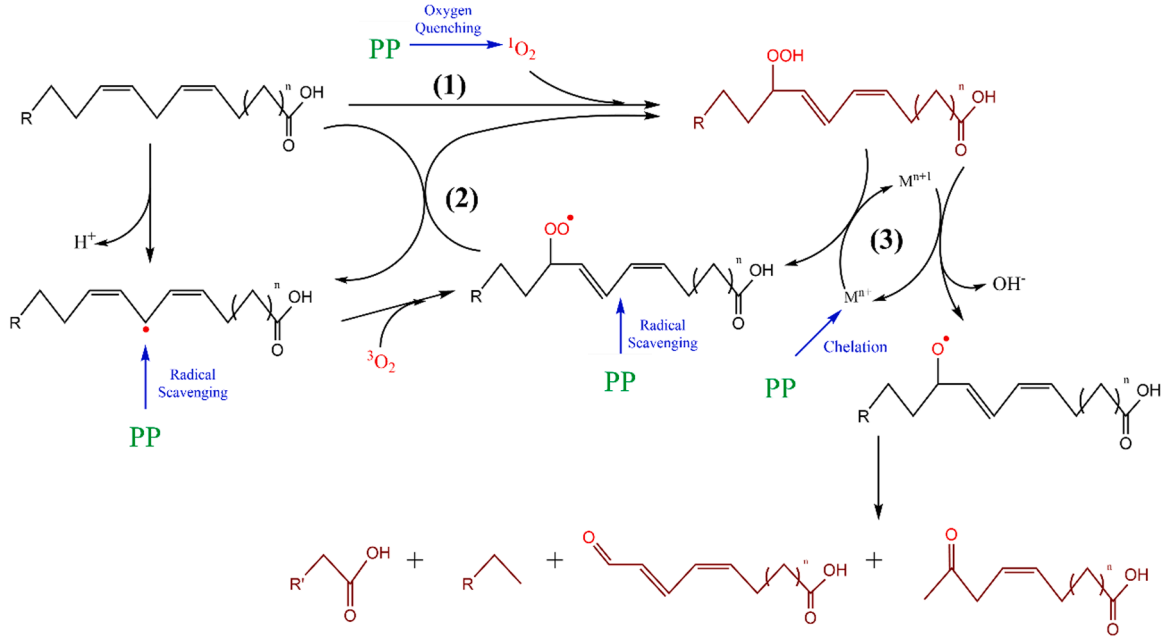

Fig. 1. Mechanism of lipid oxidation, and the antioxidant effect of polyphenolic (PP) Compounds.
The unsaturated fatty acids may undergo (1) photo-oxidation, attached by singlet oxygen, (2) autoxidation generating radical species, and (3) catalyst metal ions mediated oxidation and degeneration.
Brown compounds are oxidised products. Pathways of antioxidants by PP are highlighted in blue.

Srinivasan & Kirk, 2017).

Based on structure–function relationships, polyphenols containing aromatic rings show enhanced solubility in the oil phase, facilitating interaction with lipid molecules. Nucleophilic phenolic hydroxyl groups in the ortho or meta-position of an aromatic ring can chelate the catalyst metal ions through their lone pair electrons. Additionally, the radical intermediates of PP are more stable than alkyl radicals (L•) and peroxyl radicals, due to the dispersive effect of high energy through resonance delocalisation, and thus reduce their reactive activity. PP also exhibits radical scavenging activity, protecting fatty acids in the food matrix from oxidation (Zheng et al., 2022). *E. stolonifera* extraction at 25 μg/mL inhibited 40.81 % of the reactive oxygen species (ROS). Further purified eckol and phlorofucofuroeckol have low half-maximal inhibitory concentrations (IC_{50}) of 4.04 μM and 3.80 μM, respectively, reflecting their greater radical scavenging activity than Trolox (IC_{50} = 5.70 μM), a standard ROS scavenger (Kang et al., 2004).

Several assays measuring antioxidant activity have been developed to assess different oxidation mechanisms. The most widely used method in food science research is the Thiobarbituric acid reactive substances (TBARS) assay (Papastergiadis et al., 2012). This colorimetric assay is based on the oxidative degradation products of PUFAs (Srinivasan & Kirk, 2017). Peroxide value (PV) is an indicator of the oxidative radical chain initiation, measured by reductive substances (Srinivasan & Kirk, 2017). Unlike detecting the oxidation products, the Trolox equivalent antioxidant capacity (TEAC) assay determines the antioxidants' ability to scavenge radical cation 2,2′-azinobis (3-ethylbenzothiazoline-6-sulphonic acid), ABTS•+, the species oxidized from ABTS. (Gan & Baroutian, 2022). Similarly, 2,2-diphenyl-1-picrylhydrazyl (DPPH) is a stable radical that reacts with antioxidants (Fung et al., 2013). More directly, the reducing power of antioxidants can be measured by ferric reducing antioxidant power (FRAP) by $[Fe(CN)_6]^{3-}$ or $[Fe(CN)_6]^{4-}$ (Cofrades et al., 2010). Regarding the metal chelation capacity, Fe^{2+} and Fe^{3+} are usually used as indicators of antioxidant activity (Zhang et al., 2018). Selecting the measurement method in the food system must be carefully considered, taking into account the interfering components and the nature of the food.

3.3. Antioxidant activities of brown seaweeds

A summary of the lipid antioxidation activities of brown seaweeds is presented in Table 4, which primarily focuses on chemical assays to determine antioxidant activities. It presented only the most effective results for each species, and did not include information on separated or extracted fractions that may exhibit better activity. As shown in Table 4, very few studies have been conducted on the New Zealand brown seaweed species, with almost half of them exploring the antioxidant activity of *U. pinnatifida*. From an overall perspective, *Phaeophyceae* (such as *Macrocystis pyrifera, Polycladia indica, Fucus vesiculosus, Sargassum plagiophyllum*) have been shown to have bioactivity protecting lipids from oxidation. Among them, some species are as effective as synthetic antioxidants (BHA and BHT) or natural antioxidants (citric acid, ascorbic acid) (Chakraborty et al., 2017; Kindleysides et al., 2012; Wang et al., 2010). The addition of *S. cinereum*, however, resulted in a 125.3 % increase in ROS (Kang et al., 2004). Connan et al. (2006) reported the null effect for L. *digitata* due to their low total phenol contents. Considering the low total phenol content, its potential antioxidant activity may be below the detection threshold of the DPPH assay. One reason for the varying results in studies was the chosen solvent used for the extraction of phenolic compounds, which can impact the outcomes even when using the same assay (Gan & Baroutian, 2022; Sabeena Farvin & Jacobsen, 2013; Zhang et al., 2018). Additionally, failing to specify the final concentration of seaweed powder or the extraction used can lead to confusion, as this is a critical independent variable for bioactivity determination. To address this issue, some research utilises standard controls at different concentrations, such as Trolox, Gallic Acid, and EDTA-Na_2. If time allows, it is ideal to measure and present results in a standardized manner, such as IC_{50} or half-maximal effective concentration (EC_{50}) values, for better clarity during peer review.

4. Functionality and applications

4.1. Pharmacy applications

The outstanding bioactivity properties of these compounds have attracted pharmacological research, such as anti-diabetic, anti-inflammatory, anti-bacterial, anti-allergic, radioprotective, anti-cancer, anti-tumour, anti-proliferative, and antioxidant (Chakraborty et al., 2017; Cotas et al., 2020; Subbiah et al., 2023). Roasted *D. antarctica* is a treatment for eczema and gastrointestinal complaints by Māori locals. (Brooker & Cooper, 1987). Phlorotannin is a new star in these fields whose function may depend on the species of brown seaweed from which it is sourced. Extracted from *Ecklonia cava*, phlorotannins have a significant inhibitory effect on the three target proteins of SARS-CoV-2 (Gunaseelan et al., 2022). A mixture of polysaccharides and phlorotannins from *Ecklonia radiata* is capable of stimulating the growth of *Bifidobacterium, Lactobacillus,* and *Clostridium coccoides*, etc., and can be used as dietary supplements for gastrointestinal health (Ozogul et al., 2024). Furthermore, InSea2® is a commercial alternative to acarbose for T2DM therapy, containing phlorotannins derived from *A. nodosum* and *F. vesiculosus* (Haskell-Ramsay et al., 2018). This drug is also effective for the modulation of cognition (Haskell-Ramsay et al., 2018).

4.2. Food applications

4.2.1. Food stuffs

Brown seaweeds have been used as a biomass resource in coastal regions for animal feed for an extended period of time (Reboleira et al., 2019). Given their abundant nutrients and high growth rate, seaweeds are a sustainable alternative to conventional animal feed, balancing the sustainability and high livestock production (Polat et al., 2023). 2.5 % *Turbinaria conoides* feed supplement improved the milk yield for Murrah buffaloes (Maheswari et al., 2021). Moreover, adding phlorotannins to the feed could reduce methane emissions from ruminants, thereby mitigating the greenhouse effect. (Polat et al., 2023). When applied in aquaculture, feeds containing *Sargassum horneri* resulted in the highest growth rate for sea cucumber (*Apostichopus japonicus*) over 60 days (Li et al., 2022).

"According to FAO and WHO (2022), 48 % of seaweed production is directly consumed by humans, and 32 % is used as food ingredients. For human consumption, the richness of amino acids contributes to the unique sensory properties (such as umami), which is paid attention to by several cultures (Cofrades et al., 2010). Māori consume *Pryopia* spp. (kareng) and *Gigartina* spp. (rehia) directly as a food resource (White & White, 2020). *Laminaria, Undaria*, and Porphyra, known as kombu, wakame, and nori, are the most popular macroalgal resources for cuisine (Wheeler Thomas et al., 2021). Dried biomass is usually sold at a commercial level and requires rehydration before using in soup, salads, sushi, and condiments as a whole slice or ground powder (Y. Kumar et al., 2021). Another largely consumed category of *Phaeophyceae* is *U. pinnatifida* (Wakame), mainly in China and Japan. They are the most common species used as misosoup and side salads with tofu (Y. Kumar et al., 2021).

Several innovative food products applying brown seaweed as an ingredient have been developed in recent years. Seaweeds with natural antimicrobial activities and demonstrated health benefits have received an increasing amount of research as functional ingredients for different processing properties (e.g., texture, viscosity) (Arufe et al., 2018; Cassani et al., 2020). *A. nodosum* was added to bread at 5 % w/w as a high-fibre food and was found to have acceptable sensory attributes (Hall et al., 2010). *S. wightii* was used to formulate halwa (a kind of dessert) in dried powder form at an addition amount of 2 %– 6 % (Sumayaa & Kavitha, 2015). This species, at 1 %, provided the best

Table 4
Summarisation of some studies on brown seaweeds' lipid antioxidation activities.

Species	Origin	Solvent	Methods	Results	Control	Reference
	NZ	Water	HO• radical scavenging	77.0 %	BHT: 85.0 %	(Koh et al., 2019)
	NZ	Multiple	Reducing power @ 1 mg	86.80 % inhibition	Vitamin C: ≈95.5 % inhibition	(Mak et al., 2013)
Undaria pinnatifida	Spain	50 % MeOH	FRAP	17.6 μmol eq./g ww	Trolox	(Cofrades et al., 2010)
	NZ	Subcritical Water	ABTS	45.5 mg eq./g dw	Trolox	(Gan & Baroutian, 2022)
	NZ	MeOH	DPPH	32.1 %	/	(Fung et al., 2013)
Macrocystis pyrifera	**NZ**	Water	DPPH	92.3 % inhibition	BHT: 62.4 % @ 1mM	(Kindleysides et al., 2012)
Macrocystis integrifolia	Canada	EtOH	Reducing power @ 1 mg	3.35 μg equivalents	Ascorbic acid	(Yuan & Walsh, 2006)
Ecklonia radiata	Australia	Water	Fe^{2+} reducing power	4.4 mg GAE/g dw	Gallic Acid	(Zhang et al., 2018)
	NZ	Water	DPPH	97.2 % inhibition	BHT: 62.4 % @ 1mM	(Kindleysides et al., 2012)
Ecklonia stolonifera	Korea	MeOH	ROS inhibition @ 25 μg/mL	44.3 % inhibition	Trolox 40.4 % inhibition @ 25μg/mL	(Kang et al., 2004)
Carpophyllum flexuosum	**NZ**	Water[a]	Fe^{2+} reducing power	62.1 mg GAE/g dw	Gallic Acid	(Zhang et al., 2018)
Carpophyllum plumosum	**NZ**	Water[a]	Fe^{2+} reducing power	33.0 mg GAE/g dw	Gallic Acid	(Zhang et al., 2018)
Cystoseira nodicaulis	Ireland	80 % EtOH	FRAP	101.35 ± 0.36 μg eq./mg	Trolox	(Heffernan et al., 2015)
Himanthalia elongata	Spain	50 % MeOH	Fe^{2+} reducing power	46.8 μmol eq./g ww	Trolox	(Cofrades et al., 2010)
Himanthalia elongata	Ireland	80 % EtOH	FRAP	130.89 ± 0.45 μg eq./mg	Trolox	(Heffernan et al., 2015)
Polycladia indica	Egypt	MeOH	DPPH	≈65.7 % inhibition	Ascorbic acid: 62.4 % inhibition	(Farghl et al., 2021)
Sargassum angustifolium	Iran	70 % EtOH	Total antioxidant activity	0.045 mg equivalents/g dw	Ascorbic acid	(Hodhodi et al., 2022)
Sargassum fusiforme	China	30 % EtOH +ethyl acetate	FRAP	1.29 mg equivalents/mg	Trolox	(Li et al., 2017)
Turbinaria ornate	Egypt	MeOH	DPPH	72.5 % inhibition	Ascorbic acid: 62.4 % inhibition	(Farghl et al., 2021)
Turbinaria sp.	India	Acetone	Total antioxidant activity	0.48 mg GAE/g	Gallic Acid	(Smita et al., 2022)
Species	Origin	Solvent	Methods	Results	Control	Reference
	Iceland	Water	Fe^{2+} chelating activity @ 5 mg/mL	94 %	[b]NaY_2: 99.8 % @ 0.05 mg/mL	(Wang et al., 2009)
Fucus serratus	Ireland	80 % EtOH	FRAP	110.94 ± 0.65 μg eq./mg	Trolox	(Heffernan et al., 2015)
	Denmark	Water	DPPH	EC_{50} 8.30 μg/mL [c]	$EC_{50,BHT}$ 10.7 μg/mL	(Sabeena Farvin & Jacobsen, 2013)
Fucus distichus	Denmark	EtOH	TBARS @ 1 mg/mL	54.7 % inhibition	BHT 57.8 inhibition	(Sabeena Farvin & Jacobsen, 2013)
	Denmark	Water	DPPH	EC_{50} 8.30 μg/mL	$EC_{50,BHT}$ 10.7 μg/mL	(Sabeena Farvin & Jacobsen, 2013)
	Iceland	Water	Metal chelating activity @ 1 mg/mL	94.8 % inhibition	EDTA 50.8 % inhibition	(Hermund et al., 2015)
Fucus vesiculosus	Iceland	80 % EtOH	Fe^{2+} chelating activity @ 5 mg/mL	34.7 %	Citric acid: 21.5 % @ 5 mg/mL	(Wang et al., 2010)
	Iceland	Acetone	Fe^{2+}Reducing powder (OD_{700})	1.6 @ 2 mg/mL	Ascorbic acid: 1.6 @ 2 mg/mL (in MeOH)	(Honold et al., 2016)
	Iceland	Water	Fe^{2+} chelating activity @ 5 mg/mL	95 %	NaY_2: 99.8 % @ 0.05 mg/mL	(Wang et al., 2009)
Fucus vesiculosus	Ireland	80 % EtOH	FRAP	307.27 ± 1.22 μg eq./mg	Trolox	(Heffernan et al., 2015)
Fucus spiralis	Denmark	EtOH	Fe^{2+} reducing @ 1 mg/mL	1.6	Ascorbic acid: 2.28	(Sabeena Farvin & Jacobsen, 2013)
	Iceland	Water	Fe^{2+} chelating activity @ 5 mg/mL	79 %	NaY_2: 99.8 % @ 0.05 mg/mL	(Wang et al., 2009)
Laminaria digitata	Denmark	EtOH	TBARS @ 1 mg/mL	24.2 % inhibition	BHT 57.8 inhibition	(Sabeena Farvin & Jacobsen, 2013)
Laminaria setchellii	Canada	EtOH	Reducing activity @ 1 mg	2.57 μg equivalents	Ascorbic acid	(Yuan & Walsh, 2006)
Laminaria japonica	Korea	Oil	TEAC (ABTS)	IC_{50} 92.98 μg/mL	$IC_{50,BHT}$ 19.65 μg/mL	(Patra et al., 2015)
Laminaria hyperborea	Iceland	Water	Fe^{2+} chelating activity @ 5 mg/mL	96 %	NaY_2: 99.8 % @ 0.05 mg/mL	(Wang et al., 2009)
Species	Origin	Solvent	Methods	Results	Control	Reference
Sargassum plagiophyllum	India	EtOAc	Fe^{2+} chelating	IC_{50} 0.22 mg/mL	$IC_{50,BHA}$ 0.25 mg/mL	(Chakraborty et al., 2017)
Sargassum myriocystum	India	EtOAc	Fe^{2+} chelating	IC_{50} 0.33 mg/mL	$IC_{50,BHA}$ 0.25 mg/mL	(Chakraborty et al., 2017)
Sargassum muticum	Denmark	Water	TBARS @ 1 mg/mL	21.3 % inhibition	BHT 57.8 inhibition	(Sabeena Farvin & Jacobsen, 2013)
Sargassum sp.	India	Acetonitrile	Total antioxidant activity	0.61 mg GAE/g	Gallic Acid	(Smita et al., 2022)
Saccharina latissima	Denmark	EtOH	TBARS @ 1 mg/mL	31.3 % inhibition	BHT 57.8 inhibition	(Sabeena Farvin & Jacobsen, 2013)

(*continued on next page*)

Table 4 (*continued*)

Species	Origin	Solvent	Methods	Results	Control	Reference
	Iceland	Water	Fe^{2+} chelating activity @ 5 mg/mL	74 %	NaY_2: 99.8 % @ 0.05 mg/mL	(Wang et al., 2009)
Nereocystis leutkeana	Canada	EtOH	Reducing activity @ 1 mg	2.23μ g equivalents	Ascorbic acid	(Yuan & Walsh, 2006)
Dictyota dichotoma	Denmark	Water	TBARS @ 1 mg/mL	21.7 % inhibition	BHT 57.8 inhibition	(Sabeena Farvin & Jacobsen, 2013)
Anthophycus longifolius	India	EtOAc	HO• radical scavenging	IC_{50} 0.19 mg/mL	$IC_{50,BHA}$ 0.19 mg/mL	(Chakraborty et al., 2017)
Alaria esculenta	Iceland	Water	Fe^{2+} chelating activity @ 5 mg/mL	72 %	NaY_2: 99.8 % @ 0.05 mg/mL	(Wang et al., 2009)

[a] : Water extraction assisted by microwave, heating for 3 min at 160 °C.
[b] : NaY_2: EDTA-Na_2.
[c] : EC_{50} (effective concentration): The concentration of required sample to chelate 50 % of iron activity.

sensory acceptability in coffee drinks. (Kumar et al., 2019). 2.5 % addition of *S. marginatum* in the paste not only helped enhance the gluten network and reduce baking loss but also provided a relatively high level of antioxidant activity (Prabhasankar et al., 2010). Likewise, the pasta containing 10 % *U. pinnatifida* improved the interaction between starch and protein matrix, and its sensory properties were acceptable with a mild seaweed flavour (Prabhasankar et al., 2009; Subbiah et al., 2023). This principle of enhancing gluten networking has been applied in other baking goods. By replacing 5 % of wheat flour with *S. fusiforme* flour, cookies had better water retention capacity, which ultimately resulted in a different spread factor and breaking stress, helping them stand out in the sensory tests (Oh et al., 2020). *Treptacantha abies-marina* was used to prepare cookies and sauce at the concentrations of 3 % and 2 % w/w, respectively, as successful examples to incorporate seaweed within food (Afonso et al., 2020).

These are examples of integrating brown seaweeds in food products as a whole ingredient when the addition amount was high (2 %– 5 %), regarding it as an "additive". It would be advantageous if experiments addressed the benefits of shelf-life extension and quality-related characteristics offered by antioxidant extracts, where most consumers might consider seaweed extraction as an additive, rather than a functional ingredient. Another factor that should be paid attention to is the off-flavour caused by seaweed addition. This may be described as a distinct fishy smell by some consumers, attributed to amino acids, which hinders their ready consumption. Incorporating seaweeds into those food ingredients with volatile aroma is a strategy to increase acceptability (Kumar et al., 2019). Corsetto et al. (2020) confirmed the flavour ingredients (garlic, basil + tomato, and rosemary) can cover the off-flavour in rye snakes, according to sensory tests.

4.2.2. Food additives

Although some brown seaweeds can be used whole in food, extraction is more common for utilisation as food additives. Alginate, a type of hydrocolloid extracted from brown seaweeds, can act as a thickener, gelling agent, and stabiliser in ice cream, frozen foods, and beverages.

Phenolic compounds (phlorotannins) extracted from *Phaeophyceae* are a potential type of antioxidant for food applications. The permissible limitation of antioxidants used in food products ranges from 1 ppm to 50,000 ppm (5 %), while some are generally recognized as safe (GRAS) or are approved for general use, such as EDTA (Michael & Ash, 2008; Smith & Hong-Shum, 2011). The discussion in this part, therefore, focuses on research in which the addition amount was within this limitation (5 % w/w) in food-based systems, to achieve a longer shelf life (Table 5).

In a pure lecithin liposome system, even though the effect was weaker than 50 ppm BHT, *Turbinaria ornata*'s MeOH extraction at 100 ppm successfully decreased TBARS content throughout the 10-day experiment (Rattaya et al., 2015). New Zealand brown seaweed extractions from *E. radiata* and *M. pyrifera* were added to hoki liver oil (0.5 % w/w) before storing for 12 days at 60 °C (Kindleysides et al., 2012). The results showed that both extractions reduced PV effectively, and their antioxidant activities were comparable to BHT. For more complex food products, no matter the extraction solvent used, *F. vesiculosus* extractions have been proven to have antioxidant capacity for shelf life extension in fish-oil-enriched milk and mayonnaise (Hermund et al., 2015). Not only was PV reduced when the addition amount of F. vesiculosus extractions ranged from 0.1 % to 0.2 % w/w, but fewer secondary oxidation products were generated. Congruous results were observed when using different solvents, i.e., acetone and water (Honold et al., 2016). Furthermore, extractions can be used in meat products. The addition of *F. vesiculosus* EtOAc or 80 % EtOH extraction at 300 mg PGE/kg cod fillets helped dramatically reduce the rancidity odour, and repulse oxidation reactions within 7 days (Jónsdóttir et al., 2016; Wang et al., 2010). Polyphenols extracted from another common species, *U. pinnatifida*, also reduced the progress of oxidation significantly after a six-day storage at 4 °C. The final concentration of phenolic compounds was 200 ppm based on the weight of chicken breast (Sasaki et al., 2008).

Incorporating seaweed extraction as an antioxidant additive can also be challenging. Thermal processing is essential in food processing for value addition and longer shelf life, but it can sometimes involve severe conditions. One concern of applying seaweed extractions in food products as natural antioxidants is the degeneration of bioactive compounds caused by thermal processing (Ismail et al., 2004; Zhang & Hamauzu, 2004). It has been proven that, after thermal processing, extractions could retain their activities. Incorporating 0.01 % *E. cava* EtOAc extraction into fish oil decreased the oxidation reaction rate under accelerated oxidation conditions (60 °C) for 11 days. (Senevirathne et al., 2006), which had the same effect as 0.01 % α-Tocopherol Bleaching at 60 °C for 5 min, only reduced 35.6 % of the antioxidant ability for *S. latissimi* (Cecilie Bay Wirenfeldt, 2023). In 74 °C cooked turkey meat sausages, 400 ppm purified *Cystoseira barbata* extraction had the same effect as 450 ppm ascorbic acid. (Sellimi et al., 2017). Similarly, the antioxidant activity dropped slightly before and after extrusion processing at 140 °C when incorporating *F. vesiculosus* extractions with rye snacks (Corsetto et al., 2020). Pasta contained 5 %– 30 % *U. pinnatifida* extraction, retained around 20 % of total antioxidant activity after extrusion and drying at 75 °C for 3 h (Prabhasankar et al., 2009). Under more extreme conditions, baking processing mimicking (175 °C, 22 min) reduced 43.6 % of TPC from *S. ilicifolium* extraction. (Kaushalya & Gunathilake, 2022). Cooking minced pork patties at 180 °C to reach 72 °C internal temperature for 20 min also proved the antioxidant effect of the extraction, with less TBARS generated. (Moroney et al., 2013). Conversely, when freezing the red sea bream mince at −18 °C for up to 90 days, samples with 0.1 % brown seaweed polyphenols had parallel antioxidant capacity with ascorbic acid and α-tocopherol (Wang et al., 2017). This result is particularly meaningful for food manufacturing involving frozen storage or cold chain distribution.

Salt and metal ions, as pro-oxidants, can deteriorate the oxidation reaction when seaweed extract is added. Moroney et al. (2013) reported the null effect when using L. *digitata* extraction of oxidation in minced pork patties, at the concentration of 0.5 % w/w, during two-week

Table 5
Applications of brown seaweed extractions in food as antioxidant additives.

Species	Food Product	Addition Amount (w/w)	Processing Condition	Conclusion	Reference
Ascophyllum nodosum	Canola oil	500 ppm	16 days of storage at 60 °C	Lower Peroxide and p-anisidine values than blank control and BHT; More TBARS than control at the 12th day.	(Agregán et al., 2017)
	Milk	0.25 %, 0.5 %	Pasteurised at 63 °C, 30 min; 11 days of storage at 4 °C	Null effect or even worse (more TBARS)	(O'Sullivan et al., 2014)
Bifurcaria bifurcata	Canola oil	500 ppm	16 days of storage at 60 °C	Lower Peroxide and p-anisidine values than blank control and BHT; Less TBARS than control; similar to BHT	(Agregán et al., 2017)
Cystoseira barbata	Turkey meat sausages	400 ppm	74 °C cooked; 15 days storage at 4 °C	Reduced TBARS; The same inhibition effect as 450 ppm ascorbic acid	(Sellimi et al., 2017)
Ecklonia cava	Fish oil	0.01 %, 0.1 %, 0.5 %	11 days storage at 60 °C in darkness	0.5 % w/w had the best effect; Less oxidation product; Similar effect as 0.01 % BHT and α-tocopherol	(Senevirathne et al., 2006)
Ecklonia radiata	Hoki liver oil	0.5 %	12 days of storage at 60 °C	Reduced PV; Similar effect with BHT	(Kindleysides et al., 2012)
Fucus vesiculosus	Canola oil	500 ppm	16 days of storage at 60 °C	Lower *P*eroxide and *p*-anisidine values than blank control and BHT; Less TBARS than control; similar to BHT	(Agregán et al., 2017)
	Milk	0.25 %, 0.5 %	Pasteurised at 63 °C, 30 min; 11 days of storage at 4 °C	Null effect or even worse (more TBARS)	(O'Sullivan et al., 2014)
	Fish-oil-enriched milk	0.1 %– 0.2 %	Heated to 72 °C for 15 s +homogenised at 250 bar; 12 days of storage at 5 °C	Less secondary oxidation products (1-penten-3-one, 1-penten-3-ol, and heptanal)	(Hermund et al., 2015)
	Fish-oil-enriched mayonnaise	0.1 %– 0.2 %	28 days storage at 20 °C	Lower PV; Less secondary oxidation products (1-penten-3-one, 1-penten-3-ol, and heptanal)	(Hermund et al., 2015)
Species	Food Product	Addition Amount (w/w)	Processing Condition	Conclusion	Reference
Fucus vesiculosus	Fish-oil-enriched mayonnaise	0.15 %, 0.2 %	28 days storage at 20 °C	Lower PV; Less secondary oxidation products (1-penten-3-one, 1-penten-3-ol, and heptanal)	(Honold et al., 2016)
	Chicken breast	1 % in active film	Wrapping with active film, 25 days storage at 4 °C	Increased film tensile strength and elastic modulus; Less TBARS	(Andrade et al., 2021)
	Cod fillet	300 mg PGE/kg	8 days storage at 1 °C– 3 °C	Lower rancidity odour score; Less TBARS (dramatically)	(Jónsdóttir et al., 2016)
	Cod fillet	300 ppm	8 days storage at 1 °C– 3 °C	Lower the rancidity odour score; Less TBARS; lower PV	(Wang et al., 2010)
	Cod liver emulsion	300 mg PGE/kg	8 days storage at 1 °C– 3 °C	Higher rancidity odour score; Higher PV; Less TBARS	(Jónsdóttir et al., 2016)
	Cooked fish cake	300 ppm	Fried at 180 °C for 6 min; +Baked at 180 °C for 5 min; 28 days storage at 0 °C– 4 °C	Null effect	(Dellarosa Nicolò Dellarosa et al., 2015)
	Fish oil-enriched granola bar (single-layer emulsion)	350, 700 ppm	175 °C for 15 min in tin foil; 10 weeks of storage at 21 °C in the dark with a sealed plastic bag	Lower PV; Fewer secondary oxidation products (1-penten-3-one, 1-penten-3-ol, and 2,4-heptadienal)	(Karadağ et al., 2017)
	Fish oil-enriched granola bar (multilayered emulsion)	400 ppm	175 °C for 15 min in tin foil; 10 weeks of storage at 21 °C in the dark with a sealed plastic bag	Lower PV; Fewer secondary oxidation products (1-penten-3-one, 1-penten-3-ol, and 2,4-heptadienal)	(Hermund et al., 2016)
Laminaria digitata	Minced pork patties	0.01 %, 0.1 %, 0.5 %	Cooked: 180 °C for 20 min; Increased O_2 & CO_2 MAP; 14 days storage at 4 °C	Uncooked: Null effect Cooked: Less TBARS @ 0.5 % w/w	(Moroney et al., 2013)
Species	Food Product	Addition Amount (w/w)	Processing Condition	Conclusion	Reference
Macrocystis pyrifera	Hoki liver oil	0.5 %	12 days of storage at 60 °C	Reduced PV; Similar effect with BHT	(Kindleysides et al., 2012)
Undaria pinnatifida	Chicken breast	200 ppm	Heated to 180 °C for 10 min PVC film over-wrapped; 1 or 6 days storage at 4 °C	Reduced TABRS for both storage lengths	(Sasaki et al., 2008)

(*continued on next page*)

Table 5 (*continued*)

Species	Food Product	Addition Amount (w/w)	Processing Condition	Conclusion	Reference
	Red sea bream mince	0.1 %	90 days storage at −18 °C	Reduced TABRS; Similar effect to ascorbic acid	(Wang et al., 2017)
Turbinaria ornata	Lecithin liposome system	100, 200, 300 ppm	Chlorophyll was removed for extractions. sonicated for 2 min; 48 h at 37 °C	200 ppm had the best effect. Decreased TBARS content; Weaker effect than 50 ppm BHT	(Rattaya et al., 2015)

storage. This conclusion changed when the pork patties were cooked at 180 °C for 20 min. Fewer oxidation products were detected by the TBARS assay compared to the control group, indicating the positive effect. The null effect was also detected in cooked fish cake with the addition of 300 ppm phlorotannins during 28 days of storage, determined by PV and TBARS (Y. Nicolò Dellarosa et al., 2015). This may be attributed to fish cake processing, which underwent 180 °C frying and baking for a long time, causing the polyphenols to degenerate. One research demonstrated that the unpurified *A. nodosum* and *F. vesiculosus* containing transitional metal ions, undesirably, promoted the lipid oxidation in milk (0.25 % and 0.5 %, w/w) during an 11-day storage period (O'Sullivan et al., 2014). These challenges partially contribute to a minority of commercialised products applying seaweed extractions in food formulation as antioxidants. Other considerations may include the sensory unacceptability caused by off-flavour. Extra product development procedures are needed to assess their effects, testing a spectrum of brown seaweed extractions as antioxidants and using aromatic ingredients to cover the unpleasant flavour.

From an overall perspective, the application of brown seaweed phenolic extractions has huge prospects. However, the research is limited, not only in the quantity available but also in the type of food to which seaweed extractions are added. There is still a long way to go to educate food manufacturers about the advantages of seaweed extractions and to turn scientific research findings into tangible products. With respect to New Zealand species, *F. vesiculosus, M. pyrifera, Ecklonia* spp., and *U. pinnatifida* are attractive candidates for exploring their potential. More effort is needed to optimise extraction conditions for polyphenol compounds, further purify them, analyse the antioxidant activity of each compound, and finally convert scientific research results into market-ready products.

4.3. Other applications

Besides serving as a food or therapy, *Durvillaea poha* and *Durvillaea antarctica* are the long-standing materials used to make pōhā bags (for storage) in Māori culture. (Maggy, 2006).

With several key functional components, such as cytokines, brown seaweeds can be applied in agriculture or horticulture to promote plant growth as liquid seaweed fertiliser. *Phaeophyceae* mixture of extraction with potassium, including *Ascophyllum, Laminaria*, and *Sargassum*, can be employed as a fertiliser for globe artichoke to get a better quality. (Petropoulos et al., 2022). Several companies in New Zealand convert seaweed into plant fertiliser. "Foliar Nutrition" extracted from seaweeds from AgriSea New Zealand Seaweed Ltd. provides nutrition via leaves to plants, increasing natural sugar level, palatability, stress durability, etc. Premium Seas constructs *Undaria* framing as biofuel for mussels.

Edible coatings or films for food packaging have recently become cutting-edge areas. These films hold the advantages of conventional polymer packages, such as high resistance to mass transfer, and they are safer due to the lower risk of packaging material migration. A few studies have proved that seaweed can be used as a biopolymer to prevent the reproduction of microorganisms and oxidation, thus extending the shelf life. (Abdullah et al., 2021; Andrade et al., 2021; Zhao et al., 2022).

6. Conclusions

In a nutshell, brown seaweeds possess great potential for lipid antioxidant activity in the food industry, whose effect is even better than commonly used synthetic antioxidants, such as BHT. Their antioxidant activity mainly contributes to phlorotannins as phenolic compounds. However, antioxidant activity may vary depending on the species, growth environment, harvest season, and extraction methods. Although some trials adding phenolic compounds from brown seaweed (extraction) in food matrix to extend their shelf life were successful, fewer commercialised products are being manufactured, which indicates that applying brown seaweed (extraction) as a novel antioxidant is far from mature. The types of food that add seaweed extractions are limited to oil, mayonnaise, and meat products, and the quantity of related research was insufficient.

The seaweed industry in New Zealand is still in its infancy, with an immature supply chain and incomplete research on the nutritional components and antioxidant activities against different species. Research confirmed that brown seaweed species in New Zealand, including *Undaria pinnatifida, Ecklonia cava, Ecklonia radiata, Durvillaea antarctica, and Macrocystis pyrifera*, have promising antioxidant abilities. For the New Zealand seaweed industry to advance beyond its nascent stage, further research is required to (1) optimise and standardise phlorotannin (or phenolic compounds) extraction methods; (2) establish a comprehensive database to compare species nutrient components and their antioxidant activity systematically; and (3) explore the applications of New Zealand brown seaweed species extractions in food matrices and commercialised products, particularly the product development process. With growing investments in sustainable aquaculture, processing technology, and product innovation, brown seaweed is poised to become a commercially viable and environmentally responsible ingredient for the modern food industry.

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CRediT authorship contribution statement

Ruiyi Zhang: Writing – original draft, Validation, Investigation, Formal analysis, Conceptualization. **Ashna Khan:** Writing – review & editing, Supervision. **Jaspreet Singh:** Writing – review & editing, Conceptualization. **Lovedeep Kaur:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Conceptualization.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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