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From coastline to feed trough: unlocking *Palmaria palmata* feed potential for monogastric farm animals

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Palmaria palmata (*P. palmata*), commonly known as Dulse, is a red seaweed with increasing relevance as a potential sustainable feed ingredient for monogastric animals. It provides balanced proteins, essential amino acids, minerals, and diverse bioactive compounds with potential antioxidant and immunomodulatory effects. Unlike conventional protein sources, it can be cultivated without competing for arable land or freshwater, aligning with the goals of a circular economy. However, challenges include compositional variability, seasonal and geographic influences, and risks of contaminants such as heavy metals, iodine, and microbial hazards. Feeding trials in non-ruminants demonstrate that inclusion is feasible without adverse effects and may improve gut health and product quality; however, the evidence remains limited in scope and duration. This review consolidates current knowledge on the nutritional composition, bioactive compounds, safety concerns, processing technologies, and feeding outcomes of *P. palmata*, highlighting evidence gaps for safe inclusion levels, optimised processing, hazard management, and sustainability evaluation.

KEYWORDS

Palmaria palmata, red seaweed, dulse, processing, monogastric feed, circular feed ingredient, nutrient composition

1 Introduction

P. palmata (Linnaeus) Weber & Mohr, widely recognised by its common name dulse, is an edible red macroalga (Rhodophyta) with a long history of human and animal use across the North Atlantic (McHugh, 2003; Mouritsen et al., 2013). First described as *Fucus palmatus* by Carl Linnaeus in 1753 and later reassigned to *Palmaria* in 1805, it inhabits moderately exposed shores, attaching to rocks or other algae such as *Fucus* spp. and

Laminaria hyperborea (Stévant et al., 2023). Its fronds can grow up to 30–50 cm long, change colour seasonally from deep red in winter to greenish yellow in summer (Sears, 1998). Harvested since at least the 12th century, *P. palmata* has been consumed across Ireland, Scotland, Iceland, Norway, France, Atlantic Canada, and New England, where it was eaten fresh, dried, or incorporated into breads and stews (McHugh, 2003; Mouritsen et al., 2013). Beyond its use as food, it was also valued in folk medicine and occasionally used as livestock feed. Today, *P. palmata* is increasingly positioned within the “blue bioeconomy” as a sustainable biomass supporting circular food systems and the Sustainable Development Goals (FAO, 2018; Parodi et al., 2018; Duarte et al., 2020).

Interest in its application as feedstuff for monogastric animals has grown as part of broader efforts to identify sustainable, circular feed ingredients that can reduce dependence on imported protein sources (Makkar et al., 2016; Øverland et al., 2019). Using locally available *P. palmata* could enhance feed security, diversify raw material supply chains, and lower the environmental footprint of feed production. This advantage stems from its ability to grow in coastal environments without competing for arable land or freshwater, making it particularly attractive within circular economy frameworks. However, integrating *P. palmata* into practical feeding strategies also presents challenges, including variability in composition due to seasonality and geography, the presence of undesirable substances such as heavy metals and iodine, and the need for effective processing methods to ensure feed safety and nutrient bioavailability (Holdt and Kraan, 2011; Moroney et al., 2014; Cherry et al., 2019; Stévant et al., 2023).

The scientific literature on *P. palmata* spans nutritional composition, processing techniques, safety hazards, and its potential impacts on animal performance and health (Holdt and Kraan, 2011; Stévant et al., 2023). However, the existing evidence is fragmented across disciplines, as most compositional studies (e.g., Beacham et al., 2019) are directed towards biorefinery or bioenergy, applications, with limited investigations assessing its nutritional relevance in monogastric farm animals (Karimi, 2015; Kulshreshtha et al., 2014). These challenges make it difficult to draw firm conclusions on safe inclusion levels or consistent effects on productivity and health outcomes. There is therefore a need to consolidate available knowledge and identify research priorities that will guide future use of *P. palmata* in monogastric feeding systems.

The objective of this review is to synthesise current knowledge on *P. palmata* with a specific emphasis on its nutritional composition, bioactive compounds, processing and safety considerations, and outcomes from feeding trials in monogastric animals. Special attention is given to regulatory aspects, hazard management, and sustainability implications. By integrating these themes, this review highlights both the opportunities and the research priorities required to support the safe and effective use of *P. palmata* in monogastric nutrition.

1.1 Literature search strategy

A structured literature search was conducted to identify relevant studies on *P. palmata* and its application in monogastric nutrition. The

search was carried out using major scientific databases, including Web of Science, Scopus, PubMed, and Google Scholar. Keywords and combinations included “*Palmaria palmata*,” “dulse,” “red seaweed,” “poultry nutrition,” “monogastric feed,” “seaweed safety,” and “seaweed processing.” Publications from 1980 onwards were considered, with priority given to peer-reviewed articles but also including authoritative reports from regulatory and international organisations.

Inclusion criteria required original data or substantive discussion of nutritional composition, bioactive compounds, processing technologies, safety hazards, regulatory frameworks, or animal feeding trials. Studies on other red seaweeds were considered when direct evidence for *P. palmata* was lacking, providing contextual comparison. Exclusion criteria included studies not available in English and those lacking relevance to animal nutrition or feed safety.

This approach ensured comprehensive coverage of nutritional, functional, safety, and sustainability aspects, allowing for integration of findings across disciplines relevant to *P. palmata* in monogastric feeding systems.

2 Harvesting, processing, and quality determinants

2.1 Harvesting

The quality of red seaweeds such as *P. palmata* is strongly influenced by both harvesting method and timing. Traditionally, *P. palmata* and other seaweeds have been hand-collected during low tide from intertidal zones or gathered as drift material, a practice still common in coastal communities in Ireland, Iceland, and Atlantic Canada (McHugh, 2003; Mouritsen et al., 2013). Hand harvesting maintains frond integrity and reduces contamination by sand, shells, or epiphytes. Mechanical methods, including rakes, dredges, or cutters, have been trialled to increase yields but can damage thalli, introduce debris, and compromise natural regrowth (Mac Monagail et al., 2017).

Cultivation is increasingly recognised as a viable strategy for ensuring continuous, year-round biomass supply and enhancing the consistency of biomass quality. Successful cultivation has been demonstrated in land-based tanks from spores (Le Gall et al., 2004) and in open-water systems using seeded ropes or nets (Stévant et al., 2023). Cultivated production enables greater control over harvest timing and nutritional profile. However, large-scale cultivation remains limited, with wild-harvested material continuing to be the main source available for feed applications. This review therefore, focuses primarily on wild-harvested *P. palmata*, reflecting its current relevance and widespread availability.

2.2 Postharvest handling, drying, and processing strategies

Fresh *P. palmata* is highly perishable due to its high moisture content (~80%), making immediate postharvest treatment essential

to preserve quality for feed use. Cold storage at ~4°C can maintain colour, texture, and microbial stability for up to two weeks (Liot et al., 1993), providing a short-term option for local usage, but that is impractical for long-distance supply chains. Blast freezing at –20 to –40°C effectively halts enzymatic activity, preserves pigments and proteins, and allows flexibility in downstream processing (Fleurence, 1999; Dumay et al., 2013). Although energy-intensive, freezing is widely used to secure biomass of consistent quality for research and specialised feed applications.

Blanching, which involves briefly immersing seaweed in hot fresh water or seawater (30–95°C for 1–2 min), is a common stabilisation method used to inactivate endogenous enzymes, reduce iodine content, lower microbial loads, and preserve colour (Lüning and Mortensen, 2015; Stévant et al., 2017). While highly effective for food and feed safety, blanching may cause nutrient leaching if conditions are not carefully controlled (Nielsen et al., 2020; Akomea-Frempong et al., 2021).

Drying remains the most common strategy for preserving *P. palmata* for long-term use. Sun drying is an inexpensive and widely practised method. However, it is highly weather-dependent, difficult to standardise and carries risks of oxidation and microbial contamination (Chan et al., 1997; Fernandes and Rodrigues, 2007), making it challenging to comply with standards such as HACCP and food safety regulations. Solar dryers provide a more hygienic and controlled alternative, although their effectiveness still depends heavily on local climatic conditions (Fudholi et al., 2014a; 2014b). Convective hot-air drying (25–80°C) allows greater process control and can improve protein extractability, but higher temperatures may degrade antioxidants, polyunsaturated fatty acids, and vitamin C (Wong and Cheung, 2001a, b; Gupta et al., 2011). Freeze-drying (<– 40°C under vacuum) offers the best preservation of colour, amino acids, and other labile compounds,

yet its high cost and low scalability limit its practicality for large-scale feed production (Chan et al., 1997; Nowak and Jakubczyk, 2020).

Fermentation is also being explored as a value-adding postharvest strategy. Lactic acid fermentation can lower sodium and heavy metal contents while improving digestibility, antioxidant capacity, and the release of bioactive peptides (Marrion et al., 2003; Dumay et al., 2013; Bruhn et al., 2019). Overall, each stabilisation method presents trade-offs in terms of cost, nutrient preservation, microbial safety, and scalability. Their comparative advantages and limitations for monogastric feed applications are summarised in Table 1, which outlines the relevance of these processes for maintaining nutrient quality, ensuring feed safety, and enabling the practical inclusion of *P. palmata* in monogastric diets.

3 Nutritional profile of *Palmaria palmata*

3.1 Proximate composition

The proximate composition of *P. palmata* varies considerably depending on its state and processing method. Fresh wild fronds typically contain high moisture (78–90%), corresponding to only 10–22% dry matter (DM), with clear seasonal and geographic variation (Rødde et al., 2004). Reviews report moisture contents as high as 88% in fresh material, leaving ~12% DM, with moisture levels typically peaking in winter and spring (Stévant et al., 2023). Once dried, however, *P. palmata* becomes considerably more stable. Commercial dried products contain ~9.7% moisture (i.e., ~90.3% DM) when analysed using gravimetric methods (Campos et al., 2022). Moisture content is also influenced by the degree of drying.

TABLE 1 Postharvest stabilisation and processing methods for *P. palmata*: effects on nutrient retention, quality, and relevance for monogastric feed.

Method	Short description	Effects on quality	Relevance to monogastric nutrition	References
Cold storage	4°C, up to 2 weeks	Maintains colour, texture, and low microbial load	Preserves biomass for later drying or inclusion trials	Liot et al., 1993
Blast freezing	Rapid freezing at –20 to –40°C	Preserves pigments, proteins, and texture; halts enzymatic activity	Allows flexible storage and standardised feed ingredient supply	Fleurence, 1999; Dumay et al., 2013
Blanching	30–95°C, 1–2 min (hot water or seawater)	Reduces iodine and microbes; stabilises colour; can preserve amino acids and omega-3	Important for lowering iodine to safe dietary levels; improves palatability	Lüning and Mortensen, 2015; Stévant et al., 2017; Nielsen et al., 2020
Sun drying	Ambient exposure	Very low cost; variable quality; oxidative and microbial risks	Inconsistent nutrient quality; limited suitability for research diets	Chan et al., 1997; Fernandes and Rodrigues, 2007
Solar dryer	Enclosed chamber, passive/assisted heating	Cleaner and more hygienic than sun drying; quality depends on irradiance	Low-cost route for small-scale feed production	Fudholi et al., 2014a; 2014b
Hot-air drying	25–80°C forced air	Higher temperatures increase protein extractability but reduce antioxidants	Potentially improves protein availability but risks bioactive losses	Wong and Cheung, 2001a; Gupta et al., 2011
Freeze drying	< –40°C under vacuum	Best preservation of amino acids, fatty acids, and vitamin C; costly	Ideal for research diets to assess full nutrient potential	Chan et al., 1997; Nowak and Jakubczyk, 2020
Fermentation	Lactic acid or enzymatic processes	Lowers pH, reduces contaminants, enhances digestibility and bioactive peptide release	Enhances nutrient accessibility, prebiotic potential, and safety	Marrion et al., 2003; Dumay et al., 2013; Bruhn et al., 2019

For example, semi-dried products used for short-term storage contained ~20% moisture (~80% DM), whereas fully dried products in the same study reached ~6% moisture, corresponding to ~94% DM (Stévant et al., 2020a, b).

These findings highlight the strong influence of harvest season, processing, and storage on reported nutrient values. On a dry matter basis, *P. palmata* is a nutrient-dense red macroalga with crude protein typically ranging from 8–35% DW, placing it between cereals and conventional protein-rich feedstuffs. In a UK-based study, Beacham et al. (2019) reported *P. palmata* to contain approximately 9–18% protein, ~1% lipid, high carbohydrate, and 18–30% ash, supporting its characterisation as a moderate-protein, mineral-rich red alga. Table 2 provides a comparative overview of the proximate composition of dried *P. palmata* alongside soyabean meal, maize, and wheat, highlighting its intermediate protein content, relatively high fibre fraction, and distinctive ash levels.

3.2 Protein and amino acid composition

The crude protein (CP) content of *P. palmata* ranges from 8–25% DM, depending on season, origin, and post-harvest handling (Fleurence, 1999; Holdt and Kraan, 2011; Mišurcová et al., 2014). CP content typically peaks in winter and early spring (up to ~21.9% but declines to ~11.9% in summer and autumn, reflecting a physiological trade-off between nitrogen assimilation and carbohydrate storage during periods of rapid growth (Morgan et al., 1980; Fleurence et al., 1995; Galland-Irmouli et al., 1999). Some studies have reported values as high as 35% (Moroney et al., 2014), although such variation may also be explained by variation in environmental factors, analytical methodology, and the inclusion or exclusion of non-protein nitrogen in earlier estimates. Compared with soya bean meal (48% CP), *P. palmata* contains less overall protein but remains comparable to cereal ingredients such as wheat and maize (Premier Atlas, 2025).

A critical consideration when interpreting these values is the nitrogen-to-protein conversion factor. The conventional factor used is 6.25, which assumes that all nitrogen derives from protein, with an average nitrogen content of 16%. This is a reasonable assumption for animal feed but not for seaweeds. In *P. palmata*, a substantial proportion of nitrogen occurs in non-protein compounds such as nucleotides and other nitrogenous solutes. Thus, for untreated *P. palmata*, a factor of 4.7 has been recommended (Morgan et al.,

1980; Lourenço et al., 2002, 2004), and thus CP levels would be lower than when the standard factor is applied.

Processing can alter the ratio of protein to non-protein nitrogen, thus necessitating even lower factors (2.5–4.1) (Harnedy and FitzGerald, 2013; Stévant et al., 2017; Naseri et al., 2020). Treatments such as washing, blanching, drying, fermentation, or enzymatic hydrolysis can remove soluble nitrogen fractions or change protein solubility, thereby shifting the true protein content relative to total nitrogen. Applying reduced factors in these cases produces a more accurate estimate of the true protein and prevents misleading comparisons with soya bean meal or other conventional ingredients. Thus, careful selection of the nitrogen-to-protein conversion factor, tailored to both species and processing, is critical for generating reliable nutritional data for feed formulations.

Beyond crude protein levels, the amino acid profile of *P. palmata* is notable for its richness in essential amino acids (EAAs), which often exceed those found in animal feed (Table 3). Lysine (4.6–8.2% of CP) and methionine (1.9–2.7% of CP) are particularly abundant, exceeding levels in soya bean meal (2.95% and 0.63%) or cereals such as maize (0.23% and 0.16%) and wheat (0.32% and 0.17%) (Mišurcová et al., 2014; Galland-Irmouli et al., 1999; Morgan et al., 1980; Mai et al., 1994; Bikker et al., 2020). Branched-chain amino acids are also present at relatively high levels, with isoleucine (3.5–5.3% of CP), leucine (5.5–7.8%), and valine (5.1–6.9%) all exceeding values in soya bean meal (2.24%, 3.71%, 2.32%). Among the non-essential amino acids, aspartic acid (8.5–18.5%) and glutamic acid (6.7–13.0%) dominate, contributing to the characteristic umami flavour of *P. palmata* (Galland-Irmouli et al., 1999; Mišurcová et al., 2014). Glycine (4.9–13.3%), alanine (6.3–7.8%), and tyrosine (1.3–4.5%) are also present at higher concentrations than in conventional feedstuffs. However, some amino acids, such as cystine, histidine, and tryptophan, tend to occur at lower relative levels, which may represent potential limiting factors when formulating balanced diets.

Although the CP content of dried *P. palmata* (8–25% DM) is lower than that of soya bean meal (48.8% DM), its richness in key EAAs makes it a valuable complement to cereal-based monogastric diets where lysine, methionine, and threonine are often limiting (Table 3). In addition, enzymatic hydrolysis, especially when combined with carbohydrase such as xylanase, has been shown to enhance protein solubility and release bioactive peptides with antioxidant, antihypertensive, and antimicrobial properties, further supporting the role of *P. palmata* as both a protein source and a functional feed ingredient (Harnedy and FitzGerald, 2013).

TABLE 2 Proximate composition of dried *P. palmata* compared with soya bean meal and cereal ingredients (% DM basis).

Ingredient	DM (%)	C P (%)	Fat (%)	Fibre (%)	NDF (%)	ADF (%)	Ash (%)	References
<i>Palmaria palmata</i>	90.0	8.0–25.0	1–1.3	3.5	31.2	5.0	18.0–30	Mišurcová et al. (2014); Bikker et al. (2020); Beacham et al. (2019)
Soya bean meal (48%)	88.0	48.8	1.5	3.7	8.4	5.1	6.4	Premier Atlas (2025)
Maize	87.0	7.6	3.6	2.0	9.2	2.6	1.2	Premier Atlas (2025)
Wheat	87.0	10.7	1.6	2.2	8.6	3.5	1.5	Premier Atlas (2025)

DM, Dry matter; C P, Crude protein; NDF, Neutral detergent fibre; ADF, Acid detergent fibre.

TABLE 3 Comparative crude protein and amino acid composition of *Palmaria palmata*, soya bean meal, maize, and wheat (% of CP, DM basis).

Amino Acid	<i>P. palmata</i> (range) ¹	Soya bean meal ²	Maize ²	Wheat ²
Histidine	1.7–2.1	1.26	0.22	0.25
Arginine	5.5–6.2	3.56	0.36	0.52
Isoleucine	3.5–5.3	2.24	0.25	0.14
Leucine	5.5–7.8	3.71	0.91	0.71
Lysine	4.6–8.2	2.95	0.23	0.32
Methionine	1.9–2.7	0.63	0.16	0.17
Phenylalanine	3.7–5.2	2.41	0.46	0.59
Threonine	3.6–4.5	1.89	0.27	0.32
Tryptophan	1.4–3.0	0.65	0.06	0.07
Valine	5.1–6.9	2.32	0.36	0.46
Aspartic acid	8.5–18.5	5.56	0.51	0.56
Serine	4.0–6.3	2.46	0.37	0.49
Glutamic acid	6.7–13.0	8.74	1.37	2.94
Proline	1.8–6.4	2.46	0.68	1.02
Glycine	4.9–13.3	2.07	0.30	0.44
Alanine	6.3–7.8	3.22	0.47	0.52
Tyrosine	1.3–4.5	1.54	0.21	0.30
Cystine	1.3–2.9	0.69	0.17	0.25
Crude Protein (% DM)	8–25	48.8	7.6	10.7

¹Mišurcová et al. (2014); Mai et al. (1994); Galland-Irmouli et al. (1999); Morgan et al. (1980); Bikker et al. (2020); ²Premier Atlas (2025).

3.3 Fatty acid composition

The fatty acid profile of *P. palmata* is characterised by a relatively high proportion of saturated fatty acids (Σ SAT 38–45% of total fatty acid methyl esters, FAME), with palmitic acid (C16:0, 23–31.9%) and myristic acid (C14:0, 6.4–10.2%) as the main contributors (Mishra et al., 1993; MacArtain et al., 2007; Mæhre et al., 2014). Monounsaturated fatty acids are present at modest levels (Σ MUFA 7–10%), primarily oleic acid (C18:1 n9). Polyunsaturated fatty acids (Σ PUFA 30–40%) are largely accounted for by eicosapentaenoic acid (EPA, C20:5 n3), which accounts represents 34.3–47% of total FAME (Fleurence et al., 1994). This composition results in an exceptionally low n-6/n-3 ratio (≤ 0.1), uncommon among plant-derived feed ingredients.

In contrast, soya bean meal, maize, and wheat are lipid-poor and their fatty acid fraction is mainly linoleic acid (C18:2 n6). *P. palmata* is therefore notable for its enrichment in long-chain n-3 fatty acids, particularly EPA, highlighting its potential as a complementary n-3 source alongside conventional feedstuffs. Table 4 summarises the reported fatty acid ranges, while Figure 1 illustrates the distribution of major fatty acid classes, both based on data compiled from Mishra et al. (1993); MacArtain et al. (2007), and Mæhre et al. (2014).

3.4 Vitamins and minerals

P. palmata provides a dense mineral and vitamin profile, reflected in its ash content, which typically ranges from 12–37% (Desideri et al., 2016; Mæhre et al., 2014; Biancarosa et al., 2018; Beacham et al., 2019). Major minerals include potassium, chloride, magnesium, calcium, phosphorus, sodium, and sulphur (Desideri et al., 2016; Mæhre et al., 2014; Biancarosa et al., 2018; Beacham et al., 2019). Trace elements such as iron, zinc, manganese, copper, nickel, bromine, and selenium are also present, with Beacham et al. (2019) confirming detectable levels of iron, phosphorus, potassium, calcium, and zinc in UK-collected material. Moderate iodine concentrations (220–260 mg/kg) have been reported, which are considerably lower than in brown seaweeds, making *P. palmata* a comparatively safe iodine source for food and feed applications (Holdt and Kraan, 2011; MacArtain et al., 2007).

In addition to its mineral richness, *P. palmata* contains significant amounts of riboflavin (B2), niacin (B3), vitamin C, vitamin E, and provitamin A (Kraan, 2013; Mabeau and Fleurence, 1993). Table 5 presents the mineral composition of *P. palmata* relative to soya bean meal, maize, and wheat, highlighting its superior density of both macro- and micro-minerals compared with animal feed.

TABLE 4 Fatty acid composition of *Palmaria palmata* (% of total FAME).

Fatty Acid	(%)
Saturated fatty acids (SAT)	
C14:0 (Myristic acid)	6.4–10.2
C16:0 (Palmitic acid)	21.4–31.9
C18:0 (Stearic acid)	1.1–7.1
Total saturated fatty acids (Σ SAT)	38–45
Monounsaturated fatty acids (MUFA)	
C16:1, n7 (Palmitoleic)	1.4–5.2
C18:1, n9 (Oleic)	2.8–5.1
C18:1, n7	2.2–7.1
Total MUFA (Σ MUFA)	7–10
Polyunsaturated fatty acids (PUFA)	
C18:2, n6 (Linoleic)	0.6–1.4
C18:3, n3 (α -linolenic acid, ALA)	n.d.–1.1
C18:4, n3 (Stearidonic acid)	n.d.–2.2
C20:4, n6 (Arachidonic)	0.7–2.6
C20:5, n3 (Eicosapentaenoic acid, EPA)	34.3–50.0
Total PUFA (Σ PUFA)	30–40
n-3 PUFA (Omega-3 PUFA)	26–34.3
n-6 PUFA (Omega-6 PUFA)	1.1–2.1
n-6/n-3 (Ratio of omega-6 to omega-3 fatty acids)	0.0–0.1
Not identified	10–13

n.d., Not detected. Data sources as cited in text.

4 Bioactive compounds and functional properties

P. palmata contains a wide array of bioactive compounds, including sulphated polysaccharides, phenolics, carotenoids, phycobiliproteins, and peptides, which together underpin antioxidant, antimicrobial, immunomodulatory, and metabolic activities relevant to animal health and product quality (Holdt and Kraan, 2011; Lordan et al., 2011; Harnedy and FitzGerald, 2013; Cherry et al., 2019; Xu et al., 2024). These compounds are increasingly recognised for their potential roles in supporting gut function, modulating the immune system, and enhancing oxidative stability in livestock products. However, their concentration and activity vary considerably depending on season, harvest site, and processing method (Karsten and Wiencke, 1999; Lalegerie et al., 2024).

4.1 Polysaccharides

P. palmata is distinctive among red seaweeds in having xylan-rich cell walls, rather than the carrageenan's or agars typical of most Rhodophyta (Bjarnadóttir et al., 2018; Premarathna et al., 2024). These walls are reinforced by mixed-linked β -(1 $\rightarrow$ 3)/(1 $\rightarrow$ 4)-D-Xylans, commonly referred to as rhodymenan, which provide structural rigidity through hydrogen bonding and covalent interactions with charged glycoproteins.

Functionally, these polysaccharides act as dietary fibre, influencing gut health and nutrient utilisation (Deniaud et al., 2003). Although they display only modest antioxidant activity, largely due to associated phenolics rather than the xylan backbone, their primary nutritional significance lies in their role

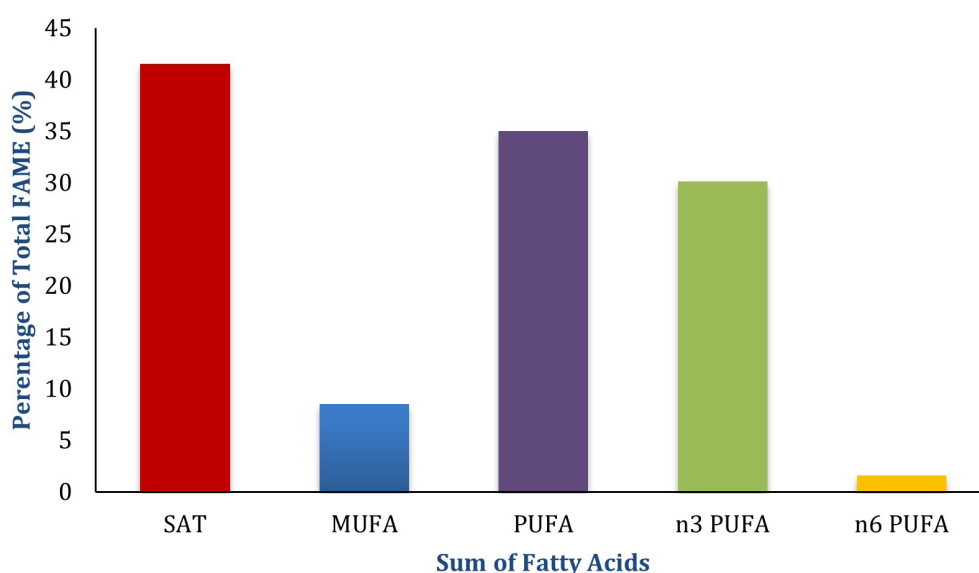


FIGURE 1

Fatty acid composition of *P. palmata* (midpoint values of reported ranges, expressed as % of total fatty acid methyl esters, FAME).

TABLE 5 Comparative mineral composition of *P. palmata*, soya bean meal, wheat, and maize.

Element	<i>P. palmata</i> ¹	Soya bean meal (48%) ²	Wheat ²	Maize ²
Macro Minerals (g/kg dry matter)				
Phosphorus (P)	2.1–2.7	6.3	2.5	2.4
Potassium (K)	28.0–95.6	21.0	4.1	3.3
Calcium (Ca)	0.861–3.6	3.0	0.4	0.30
Sulphur (S)	9.882	4.3	1.6	1.2
Magnesium (Mg)	1.2–5.3	2.8	1.4	1.0
Sodium (Na)	3.2	0.3	0.00	0.0
Chlorine (Cl)	119.3	0.9	0.9	0.6
Trace elements (mg/kg)				
Iron (Fe)	73–1009	150	55	30
Zinc (Zn)	26–42	50	30	20
Manganese (Mn)	4.1–17.4	38	30	5.0
Copper (Cu)	4.1–4.9	15.0	4.0	6.0
Selenium (Se)	0.1–0.14	0.20	0.10	0.08
Nickel (Ni)	4.2	–	–	–
Iodine (I)	220–260	0.20	0.09	0.05
Bromine (Br)	673	–	–	–

¹Desideri et al. (2016); Mæhre et al. (2014), and Biancarosa et al. (2017). ²Premier Atlas (2025).

as fermentable fibre with potential prebiotic effects, supporting beneficial microbial activity and short-chain fatty acid (SCFA) production (Harnedy and FitzGerald, 2013; De Jesus Raposo et al., 2016). In animal nutrition, the enzymatic breakdown of Xylans is particularly relevant. Xylanase supplementation in poultry diets has been shown to release xylo-oligosaccharides and increase caecal SCFA concentrations, thereby improving gut fermentation dynamics and growth performance (Craig et al., 2019). This reflects wider commercial practice, as xylanase is already widely used in monogastric diets to enhance energy release from cereal arabinoxylans, with additional evidence that xylo-oligosaccharides can support gut barrier integrity and immune modulation (Craig et al., 2019). However, direct studies on *P. palmata* xylans remain limited, and most functional inferences are extrapolated from studies on cereal arabinoxylans (e.g., from wheat, maize, and barley) rather than from *P. palmata* itself. Such findings highlight the potential value of *P. palmata* Xylans as biofunctional feed components when combined with targeted enzymatic strategies.

Alongside structural polysaccharides, *P. palmata* also accumulates floridean starch as its principal storage carbohydrate, consistent with other red algae. Floridean starch is an amylopectin-like glucan, consisting of α -(1→4)-linked chains with α -(1→6) branches but lacking amylose, and is deposited in the cytoplasm rather than plastids (Usov, 2011). While less studied in the context of nutrition, floridean starch contributes to the overall carbohydrate

pool of *P. palmata* and represents a potential source of digestible energy in feed applications.

4.2 Polyphenols and pigments

P. palmata contains a range of polyphenolic compounds, including tannins, flavonoids (catechins, flavonol derivatives), and phenolic acids such as gallic acid derivatives and hydroxycinnamic acids, which underpin its antioxidant and antimicrobial activities (Yuan et al., 2005; Gupta and Abu-Ghannam, 2011); Yuan and Macquarrie, 2015). Alongside these, *P. palmata* is rich in pigments that contribute both to functional bioactivity and product quality. These include carotenoids (β -carotene, lutein, zeaxanthin, violaxanthin, antheraxanthin), chlorophyll-a, and phycobiliproteins (notably R-phycoerythrin and phycocyanin) (Romay et al., 2003; Sekar and Chandramohan, 2008; Beacham et al., 2019).

R-phycoerythrin can represent a substantial fraction of soluble protein, acting as both a natural colourant and an antioxidant (Dumay et al., 2013). Carotenoids and chlorophylls contribute to antioxidant capacity and nutritional value, while phycobiliproteins add both bioactivity and potential for functional food applications. These pigments have demonstrated relevance in animal feeding trials, where they contribute to yolk pigmentation in poultry and

flesh coloration in fish such as salmon, as well as enhancing oxidative stability (Moroney et al., 2014, 2015). In addition, *P. palmata* produces mycosporine-like amino acids (MAAs), such as shinorine and palythine, which function as UV-protective and antioxidant compounds; however, their occurrence is strongly seasonal, and their effects in livestock models have not yet been evaluated (Karsten and Wiencke, 1999; Lalegerie et al., 2024). From an applied perspective, seaweed pigments also offer potential as natural colourants in poultry and aquaculture feeds, reducing reliance on synthetic additives.

Together, phenolics and pigments inhibit lipid peroxidation, scavenge free radicals, and may modulate gut redox balance, supporting their role in maintaining tissue integrity and improving food product quality (Cox et al., 2010; Moroney et al., 2015). When used as seaweed extracts, their recovery rate and stability are strongly influenced by processing. Enzyme-assisted extraction enhances the recovery of phenolics and pigments, whereas high-temperature drying can degrade bioactivity (Harnedy and FitzGerald, 2013; Yuan and Macquarrie, 2015; Subbiah et al., 2023). Nevertheless, the bioavailability and *in vivo* activity of *P. Palmata* phenolics and pigments in monogastrics remain underexplored, representing an important research gap.

4.3 Peptides and other bioactive compounds

Enzymatic hydrolysis of *P. palmata* proteins produces bioactive peptides with demonstrated antioxidant, antihypertensive and antidiabetic activities (Harnedy and FitzGerald, 2011; Harnedy and FitzGerald, 2013). Antimicrobial properties have been reported in other macroalgal species, but evidence specific to *P. palmata* is limited, and immunomodulatory roles are supported only by preliminary *in vitro* studies rather than animal trials. The generation and functionality of these peptides are highly dependent on protease selection and hydrolysis conditions, as methods optimising overall protein yield may not necessarily maximise bioactive potential (Harnedy and FitzGerald, 2013; Echave et al., 2022). Although such peptides are often proposed as natural alternatives to antibiotic growth promoters in livestock diets, this application remains largely theoretical, with limited direct evidence from feeding trials. Much of the supporting data instead comes from studies on polysaccharides in related red seaweeds (Cian et al., 2015). Other bioactive molecules present in *P. palmata* include the osmolyte floridoside, which has antioxidant and stress-protective roles, and polar lipids such as glycolipids and sulfolipids enriched with eicosapentaenoic acid (EPA), which have demonstrated anti-inflammatory and bioactive properties *in vitro* (Kirst, 1990; Rødde et al., 2004; Mæhre et al., 2014). While promising, these compounds have not yet been assessed in animal feeding trials. Looking ahead, targeted enzymatic hydrolysis and fractionation strategies could enable the production of defined peptide or lipid fractions with functional properties, but scaling these approaches for feed applications remains a challenge. The principal bioactive classes identified in *P. palmata*, together with their functions and the extent

of evidence available from *in vitro* assays and livestock studies, are summarised in Table 6.

4.4 Derived products and emerging applications in animal nutrition

Beyond direct dietary inclusion, several value-added products derived from *Palmaria palmata* have been explored for their potential in animal nutrition and other bio-based applications. Through targeted processing and fractionation, *P. palmata* can yield ingredients with distinct nutritional and functional roles that align with circular bioeconomy principles.

Protein concentrates and hydrolysates, produced through enzymatic extraction, contain approximately 45–50% protein with improved digestibility compared to raw seaweed. These fractions are rich in essential amino acids and bioactive peptides exhibiting amongst others antioxidant properties, making them potential partial substitutes for fish or soybean meal in monogastric feeds (Harnedy and FitzGerald, 2013). The polysaccharide-rich xylan fraction, when included in pig diets at 5%, enhances hindgut fermentation and short-chain fatty acid production without increasing digesta viscosity, suggesting its prebiotic potential (Hoebler et al., 2000; Bobin-Dubigeon et al., 1997).

Further enzymatic extraction and cell-disruption techniques have enabled the recovery of bioactive and nutrient-dense fractions from *P. palmata*. Protease-based extraction (using Alcalase®, Flavourzyme®, and Formea® Prime) yields protein-rich, water-soluble extracts enriched with amino acids and phenolic compounds that display antioxidant, antidiabetic, and anti-obesity activities, supporting their use as functional feed ingredients (Ghelichi et al., 2025). Similarly, pulsed electric field and enzymatic-assisted fractionation produce a protein-rich pellet suitable for animal feed and a sugar–mineral-rich supernatant that may be valorised in agricultural applications (Maribu et al., 2024).

Moreover, thermolysin-digested water extracts (d-DWE) of *P. palmata* contain bioactive compounds derived from phycobiliproteins and chlorophyll a with strong anti-inflammatory activity. These extracts suppress proinflammatory mediators such as nitric oxide, interleukin-6, and tumour necrosis factor- α *in vitro* and reduce inflammation *in vivo*. A novel peptide (LRDGEILRY) derived from the phycoerythrin β -chain and chlorophyll degradation products (e.g., pheophorbide a) was identified as a key contributor (Lee et al., 2017; Sakai et al., 2011; Subramoniam et al., 2012). The thermally stable, water-soluble nature of these compounds highlights *P. palmata* as a promising source of bioactive ingredients suitable for functional feed and nutraceutical formulations.

Beyond food and feed applications, *P. palmata* extracts are also utilised in the cosmetic industry due to their bioactive and antioxidant properties. Commercial products such as *P. palmata* extract and powder are incorporated into moisturisers, serums, and anti-ageing formulations for their hydrating and anti-inflammatory effects. For example, Densinaria™, a *P. palmata*-derived ingredient, is used in hair-care products to improve strength and volume. These

TABLE 6 Bioactive compound in *Palmaria palmata*, their main functions, and supporting evidence.

Category	Bioactive class	Key examples	Main functions	Evidence	References
Polysaccharides	Xylans	β -(1→3)/(1→4)-D-Xylans	Dietary fibre; limit digestibility; enzyme target	↑ Nutrient release (<i>in vitro</i> ; <i>in vivo</i>)	Deniaud et al. (2003); Harnedy and FitzGerald (2013); Beacham et al. (2019)
Polyphenols & Pigments	Phenolics	Tannins, flavonoids, gallic acid derivatives	Antioxidant; antimicrobial	Broilers: ↑ oxidative stability & performance	Yuan et al. (2005); Cox et al. (2010)
	Phycobiliproteins	R-phycoerythrin, phycocyanin	Antioxidant; pigmentation	Layers: ↑ yolk colours; Salmon: ↑ flesh redness, antioxidant status	Dumay et al. (2013); Moroney et al. (2014)
	Mycosporine-like amino acids	Shinorine, palythine	UV protection; antioxidant	Seasonal presence in <i>P. palmata</i> ; no livestock trials	Karsten and Wiencke (1999); Lalegerie et al. (2024)
	Carotenoids	Lutein, zeaxanthin, β -carotene	Antioxidant; colouration; oxidative stability	Layers: ↑ yolk colour; improved product quality	Moroney et al. (2014); Beacham et al. (2019)
	Chlorophylls	Chlorophyll a, chlorophyll b	Antioxidant; light-harvesting pigments	Evidence <i>in vitro</i> ; role in oxidative stability	Gupta and Abu-Ghannam (2011); Beacham et al. (2019)
Peptides & Others	Protein hydrolysates/peptides	Antihypertensive, antioxidant	Antihypertensive; antioxidant; potential antimicrobial	Demonstrated <i>in vitro</i> only	Harnedy and FitzGerald (2013)
	Osmolytes	Floridoside	Antioxidant; stress protection	Not yet tested in livestock	Kirst (1990); Rødde et al. (2004)
	Polar lipids	Glycolipids, sulfolipids; EPA-rich fractions	Anti-inflammatory; enrich FA profile	<i>In vitro</i>	Mæhre et al. (2014)

↑, increase; FA, fatty acids; EPA, eicosapentaenoic acid; AA, Amino acids.

applications illustrate the broad biotechnological potential of *P. palmata* and support its further valorisation across multiple sectors, including cosmetics, nutraceuticals, food and feed (SpecialChem, 2024; CosmileeEurope, 2025).

4.5 Cross-reactivity and allergic responses to *Palmaria palmata*

Allergic reactions to edible macroalgae are rare, but the increasing use of red seaweeds in food and feed formulations has drawn attention to their potential to cause hypersensitivity in susceptible individuals. Within this group, species such as *P. palmata*, *Porphyra* spp., and *Chondrus crispus* have been implicated in immunoglobulin E (IgE)-mediated allergic reactions (James et al., 2023). Although reported cases remain infrequent, and biological relevance to monogastric farmed animal application is yet to be established, these examples demonstrate that red algal constituents can act as allergenic triggers through carbohydrate or protein structures capable of eliciting immune recognition.

Carrageenans from *P. palmata* and other red algae contain alternating galactose residues that include the α -gal epitope Gal α 1-3Gal β 1-4GlcNAc-R (Macher and Galili, 2008). This carbohydrate structure is recognised by anti-Gal antibodies in humans and has been linked to α -gal syndrome, a delayed allergic reaction to mammalian meat (Steinke et al., 2015). Carrageenan exposure has

been shown to activate proinflammatory pathways, including Toll-like receptor 4 and NF- κ B signalling, leading to cytokine release and intestinal inflammation in human colonic epithelial cells (Borthakur et al., 2007; Tobacman, 2001). Clinical observations have reported hypersensitivity reactions such as urticaria and gastrointestinal distress following carrageenan ingestion (Kular et al., 2018), supporting its potential to act as a food allergen in susceptible individuals.

In addition to polysaccharide-associated epitopes, red seaweed proteins may also trigger immune responses. *Porphyra tenera* (nori), a red algal species closely related to *P. palmata*, contains tropomyosins homologous to those found in crustaceans, which are major shellfish allergens associated with extensive IgE cross-reactivity (Motoyama et al., 2007; Yang et al., 2025). This similarity raises the possibility that *P. palmata* proteins may also cross-react with IgE antibodies in individuals sensitised to shellfish allergens. Furthermore, contamination during wild harvest or aquaculture can introduce small marine invertebrates containing tropomyosin and other allergenic proteins, compounding the risk of allergic reactions (Lopata et al., 2010; Hajeb and Selamat, 2012).

Although direct evidence of *P. palmata*-specific allergy is limited, available studies collectively indicate that red seaweeds possess both carbohydrate and protein structures capable of eliciting immune responses. Further research is needed to characterise these allergenic determinants and ensure the safe incorporation of red macroalgae into food and feed applications.

5 Regulatory framework and feed safety

In the EU, seaweeds used as feed materials are regulated under Directive 2002/32/EC (2002a) to control undesirable substances in animal feed. For red seaweeds, such as *P. palmata*, the most relevant legally controlled chemical hazards are heavy metals and iodine, while microbiological, viral, and physical hazards are managed under general hygiene law and national specifications.

The inclusion of seaweeds in animal feed is formally recognised under Regulation (EC) No 767/2009, provided that products meet established hygiene and safety standards (European Commission, 2009). Directive 2002/32/EC sets maximum levels for undesirable substances, including cadmium, lead, mercury, and arsenic, an

important consideration for red seaweeds given their ability to accumulate minerals (European Commission, 2002a; Banach et al., 2020). Tables 7a, b summarise the regulatory and safety considerations for *P. palmata* as a feed ingredient.

Among these hazards, iodine is a critical factor, as concentrations in *P. palmata* often exceed food guidance thresholds, which do vary between countries (e.g., 2,000 mg/kg dry weight in France versus 20 mg/kg in Germany). Excess iodine in poultry diets can impair thyroid function, reduce hatchability, and elevate residues in eggs and meat (Teas et al., 2004; Makkar et al., 2016). Biotoxins also warrant attention: *P. palmata* contains the neurotoxic amino acid kainic acid, with levels ranging from trace amounts to approximately 560 µg/g dry weight (Jørgensen and Olesen, 2018). In addition, epiphytic dinoflagellates such as

TABLE 7A Summary of key chemical hazards associated with *P. palmata* as a feed ingredient.

Hazard/Parameter	Regulatory guidance	Relevance to <i>Palmaria palmata</i>	Poultry implications	References
Heavy metals (Cd, Pb, Hg, As)	Directive 2002/32/EC: Cd ≤ 1 mg/kg (complete feed, 12% moisture); Pb ≤ 10 mg/kg; Hg ≤ 0.1 mg/kg; As ≤ 40 mg/kg (total); inorganic As ≤ 2 mg/kg (for <i>Hizikia fusiforme</i>)	<i>P. palmata</i> can accumulate Cd and As; generally low in Hg; Pb varies with environment	Chronic exposure may impair growth and egg quality; Cd accumulates in liver/kidneys As may affect immunity and gut health	European Commission (2002a, b); Holdt and Kraan (2011); Banach et al. (2020)
Iodine	EFSA (2013): ≤ 3 mg/kg complete feed for laying hens; ≤ 2 mg/kg for dairy cows; France (ANSES, 2018): ≤ 2000 mg/kg DW; Germany: ≤ 20 mg/kg DW	<i>P. palmata</i> typically moderate iodine vs kelps: levels vary with source; soaking/boiling reduces iodine	Excess iodine alters thyroid hormones, reduces hatchability, leaves residues in eggs/meat	EFSA (2016); ANSES (2018); MacArtain et al. (2007)
Biotoxins	No EU limits for seaweed; Codex guideline values for some toxins	<i>P. palmata</i> may contain kainic acid; epiphytic dinoflagellates (e.g., <i>Ostreopsis</i>) can introduce additional toxins	Unlikely at practical inclusion levels; source monitoring recommended	Stévant et al. (2017); Jørgensen and Olesen (2018)
Persistent organic pollutants (POPs) & microplastics	No seaweed-specific EU limits; general POPs limits apply to feed (dioxins, PCBs)	Low to moderate levels, depending on site; microplastic contamination is possible	Potential long-term contaminant exposure: reduced palatability if particles are present	Banach et al. (2020); FSAI (2020)

Cd, cadmium; Pb, lead; Hg, mercury; As, arsenic; DW, dry weight; POPs, persistent organic pollutants; PCBs, polychlorinated biphenyls; EFSA, European Food Safety Authority.

TABLE 7B Biological and physical hazards associated with *P. palmata* in monogastric feed.

Hazard/Parameter	Regulatory guidance	Relevance to <i>Palmaria palmata</i>	Poultry implications	References
Microbiological hazards	<i>Salmonella</i> & <i>Listeria monocytogenes</i> absent in 25 g (EU Reg. 2073/2005); France: mesophilic aerobes <10 ⁵ CFU/g; faecal coliforms <10 CFU/g	Pathogens occasionally detected in raw seaweeds (e.g., <i>Salmonella</i> , <i>Listeria</i> , <i>Vibrio</i>)	Risk of carcass/egg contamination; mitigated by blanching, drying, HACCP	European Commission, 2005; Blikra et al. (2019); ANSES (2018);
Viral hazards	HACCP under EU food/feed hygiene law; no seaweed-specific criteria	Norovirus and hepatitis E reported in edible seaweeds; not poultry pathogens	No poultry infection shown, but feed chain contamination risk	Sakon et al. (2018)
Physical hazards	HACCP prevention/removal	Sand, shells, plastic fragments may occur during harvest/processing	May reduce intake, damage beak/gizzard if sharp particles present	FSAI (2020)
Processing safety	GMP; HACCP	Blanching/drying reduces microbial and iodine hazards, but may leach nutrients	Safe processing lowers microbial/chemical risks and improves feed safety	Stévant et al. (2017); FAO (2020)

CFU, colony-forming units; HACCP, Hazard Analysis and Critical Control Points; GMP, Good Manufacturing Practice; EU, European Union.

Ostreopsis can colonise seaweed surfaces and introduce further toxins (Rhodes et al., 2000; Monti et al., 2007).

Microbiological hazards, including *Salmonella*, *Listeria monocytogenes*, and *Vibrio* spp., as well as viral agents such as norovirus and hepatitis E virus, have been reported in minimally processed edible seaweeds (Kusumi et al., 2017; Sakon et al., 2018). Physical contaminants, including microplastics, shell fragments, and sand, are also documented in harvested biomass (FSAI, 2020).

Collectively, these risks emphasise the importance of HACCP-based hygiene management, validated processing methods (e.g., blanching, drying, fermentation), and site-specific monitoring to ensure compliance with EU/UK legislation and safe inclusion of *P. palmata* in poultry diets.

6 Feeding trials in poultry and aquaculture species

While regulatory frameworks establish safety boundaries, feeding trials provide essential evidence of how seaweeds function as practical feed ingredients by identifying safe upper limits, that is, inclusion levels at which no significant negative impacts on production parameters are observed. Several red seaweeds have been evaluated in poultry with variable but informative outcomes. Across studies, low dietary inclusion levels of red seaweeds appear well tolerated, whereas higher levels can have mixed effects depending on species. For example, *Polysiphonia* spp. at 1.5–3% of the diet had no effect on duck growth, but a much higher level (26.4%) reduced feed efficiency in broilers (El-Deek and Brikaa, 2009a, b). In quails, supplementation with the red alga *Gracilariopsis persica* at 1–5% of the diet did not impair growth or egg production but improved egg quality by lowering serum and yolk cholesterol, reducing yolk malondialdehyde concentrations, and enhancing lipid-related indices such as the ratio of high-density lipoprotein to low-density lipoprotein cholesterol (Abbaspour et al., 2015). Similarly, in layers, dietary inclusion of the red seaweeds *Chondrus crispus* and *Sarcodiotheca gaudichaudii* at 1–2% improved egg weight and feed efficiency, while also enhancing gut health through increased counts of beneficial lactic acid bacteria and reduced coliforms such as *Escherichia coli* (Kulshreshtha et al., 2014). Collectively, these examples highlight the broader potential of red seaweeds as functional feed ingredients, though outcomes vary with inclusion level and host species.

Within this broader context, targeted studies using *P. palmata* remain relatively limited in number but consistently demonstrate nutritional and functional benefits. In broilers, very low inclusion (0.05–0.25%) improved body-weight gain, feed efficiency, dry matter digestibility, gut microbial balance (increase *Lactobacillus*, decrease *E. coli* and *Salmonella*), and reduced emissions of ammonia and hydrogen sulphide (Balasubramanian et al., 2021). At slightly higher levels (0.6–3.0%, optimum ~1.8%), *P. palmata* enhanced villus morphology and stimulated immune markers such as plasma IgA, supporting gut integrity and systemic immunity (Karimi, 2015). In layers, supplementation with seaweed meal at 2% of the diet improved yolk pigmentation and oxidative stability,

although longer-term effects on egg production remain to be confirmed (Borzouie et al., 2020). The study also examined interactions with genetic strain (Lohmann Brown vs. Lohmann LSL-Lite) and heat stress, providing additional insights into context-dependent responses. Under both thermoneutral and heat-stress conditions, seaweed inclusion enhanced yolk colour intensity, reflecting deposition of algal pigments, and reduced yolk lipid peroxidation, suggesting a protective antioxidant effect. However, production parameters such as feed intake, egg output, and feed conversion ratio were not significantly altered. Plasma biochemical profiles showed some modulation, including lower triglyceride concentrations in certain treatment groups, but no adverse changes in liver enzymes or hematological indices were observed. These results suggest that moderate dietary inclusion of seaweed can enhance specific egg quality traits and lipid stability without compromising performance, though further research is needed to establish dose–response relationships, persistence of effects over extended laying cycles, and whether benefits differ across strains or environmental conditions. Evidence from aquaculture reinforces these outcomes, with studies in Atlantic salmon showing that dietary inclusion of dried *P. palmata* at levels up to 15% sustained normal growth and feed efficiency while enhancing fillet pigmentation through the deposition of red algal pigments (Moroney et al., 2015).

Overall, the available evidence indicates that *P. palmata* can be safely incorporated at low to moderate levels in poultry diets, improving growth, gut health, immunity, and product quality. Responses are dose-dependent, with inclusion above ~5% likely to reduce palatability and digestibility due to high fibre content (Holdt and Kraan, 2011; Stévant et al., 2017). Table 8 summarises feeding trials with *P. palmata* and other red seaweeds across monogastric species. Results for *P. palmata* are consistently positive, showing improvements in performance, gut morphology, immune responses, and product quality at practical inclusion levels. In contrast, outcomes with other red seaweeds are more variable and appear influenced by species, dose, and processing method. Together, these findings highlight the promising but underexplored role of *P. palmata* in sustainable poultry and monogastric nutrition.

To realise this potential, further well-controlled studies are needed to refine safe and effective inclusion levels, explore interactions with feed enzymes such as xylanase, and assess long-term impacts on performance, food safety, and product quality. Importantly, feeding trial outcomes must also be considered alongside the regulatory and safety concerns outlined in Tables 7a, b, since processing and hazard management will ultimately determine the feasibility of *P. palmata* as a commercial feed ingredient.

7 *Palmaria palmata* and the gut microbiome

Research on the impact of *P. palmata* on the poultry gut microbiota remains limited, with only a handful of controlled

TABLE 8 Feeding trials with *P. palmata* and other red seaweeds in poultry/aquaculture species.

Animal/Species	Inclusion (%)	Duration	Form	Main effects	References
Broilers (<i>Halymenia palmata</i>)	0.05–0.25	42 d	Meal	↑ BW gain, FCR, DM digestibility, villus height, Lactobacillus; ↓ <i>E. coli</i> , <i>Salmonella</i> , faecal NH ₃ & H ₂ S	Balasubramanian et al. (2021)
Broilers (<i>Palmaria palmata</i>)	0.6–3.0 (opt. ~1.8)	42 d	Meal	↑ Ileal villus size, serum IgA, Lactobacillus; under stress-maintained gut morphology & immunity	Karimi (2015)
Atlantic salmon (<i>Palmaria palmata</i>)	0–15	10 wks.	Biomass	Normal growth & FCR; ↑ fillet pigmentation; no adverse effect on quality	Moroney et al. (2015)
Ducks (<i>Polysiphonia</i> spp.)	1.5–3	Starter	Meal	No growth effect	El-Deek and Brikaa (2009b)
Broilers (<i>Polysiphonia</i> spp.)	26.4	14 d	Meal	↓ Feed efficiency	El-Deek and Brikaa (2009a)
Layers (<i>Chondrus crispus</i> & <i>S. gaudichaudii</i>)	0.5–2	67 wks.	Meal	↓ FCR, ↑ egg weight, better gut microbiota	Kulshreshtha et al. (2014)
Layers (<i>Chondrus crispus</i>)	3	21 d (short); 41 wks. (long)	Meal	Short: ↓ FI, BWG, FCR. Long: altered plasma proteins & enzymes (↓ albumin, ↑ GGT); minimal effect on performance	Borzouie et al. (2020)
Quails (<i>Gracilaria persica</i>)	1–5	5 wks	Meal	No growth impairment; replaces SBM/corn	Abbaspour et al. (2015)

BW, body weight; FCR, feed conversion ratio; DM, dry matter; IgA, immunoglobulin A; IgG, immunoglobulin G; NH₃, ammonia; H₂S, hydrogen sulphide; wks., weeks; d, days.
↑ increase and ↓ decrease.

feeding trials currently available. Consequently, much of the mechanistic understanding is derived from mammalian and aquaculture models, which nevertheless provide valuable insights into how *P. palmata* polysaccharides, phenolics, and peptides may influence microbial ecology and host responses.

In mammals, Yousof et al. (2023) demonstrated that daily oral supplementation with an aqueous *P. palmata* extract at 600 mg/kg body weight in a cuprizone-induced multiple sclerosis (MS) mouse model markedly altered gut microbial communities, as assessed by 16S rRNA gene sequencing. The extract was administered continuously across both demyelination and remyelination phases to maintain exposure to *P. palmata*-derived bioactives. Supplementation increased the Firmicutes/Bacteroidetes ratio, which is often associated with improved energy harvest and intestinal health, and promoted the growth of beneficial lactic acid bacteria such as *Lactobacillus* and *Bifidobacterium*. These taxa are well recognised for their ability to produce short-chain fatty acids (SCFAs), maintain epithelial integrity, and exert systemic anti-inflammatory effects. At the same time, the intervention suppressed potentially pathogenic taxa, including pro-inflammatory *Proteobacteria*, which are frequently elevated in dysbiosis linked to neuroinflammation.

The magnitude of these microbiome shifts varied with both the age of the animals and stage of disease, with younger mice and those in the early phase of MS showing the most pronounced enrichment of beneficial taxa. This suggests that the prebiotic and immunomodulatory effects of *P. palmata* may be most effective when applied preventively or during the early onset of inflammatory processes, rather than once dysbiosis and tissue damage are firmly established. Importantly, these microbial changes were accompanied by reductions in neuroinflammatory markers and improvements in clinical outcomes, directly linking modulation of the gut microbiome with systemic and neurological benefits.

However, not all studies have shown significant effects. Pinna et al. (2021) supplemented adult dog diets with a mixed seaweed preparation that included *P. palmata* at about 1.5% of dietary dry matter. At this inclusion level, no significant effects were detected on faecal microbiota composition, faecal secretory IgA, or apparent nutrient digestibility. The authors suggested that the lack of measurable response likely reflected several interacting factors: the relatively low dietary inclusion, potentially below the threshold required to deliver fermentable polysaccharides to the colon; the stable and resilient nature of the adult canine gut microbiota, which often resists dietary perturbation unless exposed to higher doses or longer feeding periods; and methodological limitations, as the study relied on qPCR targeting a restricted panel of bacterial groups rather than broader high-throughput sequencing approaches. These considerations imply that the absence of observed effects was due to host- and study-specific constraints, rather than an inherent lack of functional potential in *P. palmata*.

By contrast, aquatic models provide more consistent evidence of microbiome modulation. Gobet et al. (2018) conducted a year-long trial in European abalone (*Haliotis tuberculata*), in which animals were maintained on monospecific diets composed entirely of *P. palmata*. This high-level exposure offered the gut microbiota continuous access to *P. palmata* polysaccharides as the sole carbohydrate substrate. Under these conditions, distinct microbial enrichments were observed, notably of taxa such as *Polaribacter* and *Pseudahrensia*, which possess carbohydrate-active enzymes (CAZymes) capable of degrading complex algal polysaccharides. The strong dietary effects in abalone reflect their evolutionary adaptation as specialist macroalgal grazers with gut microbiota highly responsive to seaweed-derived glycans. These findings underscore the contrast between low-inclusion studies in terrestrial omnivores, which may fail to detect microbial shifts,

and high-exposure models in herbivorous or algivorous species, which clearly demonstrate *P. palmata*'s potential as a selective microbial substrate.

8 Challenges and mitigation strategies

Despite its nutritional potential, several challenges constrain the inclusion of *P. palmata* in animal diets. A major issue is compositional variability, with protein, lipid, and ash contents shifting according to season, harvest site, and processing method (Makkar et al., 2016). Protein, lipid, and ash contents can fluctuate widely, complicating consistent formulation. Mitigation requires batch-specific compositional analyses and adoption of standardised nitrogen-to-protein conversion factors (Morgan et al., 1980; Lourenço et al., 2002, 2004; Holdt and Kraan, 2011).

High ash and mineral content, notably sodium, potassium, and iodine can disrupt electrolyte balance or exceed dietary thresholds (Mæhre et al., 2014; Stévant et al., 2017). Pretreatments such as soaking, blanching, or partial extraction can lower mineral loads, while balanced formulation may offset residual risks (Nielsen et al., 2020; Akomea-Frempong et al., 2021).

Digestibility is another constraint, as the polysaccharide-rich cell wall (cellulose, Xylans, sulphated galactans) resists enzymatic breakdown in monogastrics (Fleurence, 1999; Cherry et al., 2019). Enzyme supplementation (e.g., Carbohydrases, xylanases) or fermentation can enhance nutrient release and bioactive peptide recovery, thereby improving both nutritional value and functional potential (Harnedy and FitzGerald, 2013; Øverland et al., 2019).

Finally, safety concerns remain central. *P. palmata* may accumulate heavy metals (Cd, Pb, Hg, As) or excess iodine, and can carry physical (shell, microplastics) or microbial (*Listeria*, *Salmonella*) hazards (Banach et al., 2020; Blikra et al., 2019; Cho and Rhee, 2020). Mitigation requires HACCP-based controls, careful site selection, validated processing methods, and strict regulatory compliance (ANSES, 2018; FSAI, 2020).

Collectively, these mitigation strategies highlight the importance of factors to consider when integrating *P. palmata* into monogastric feeding systems through a combination of processing optimisation, analytical monitoring, and targeted feed formulation approaches to ensure both safety and efficacy.

9 Conclusions and research priorities

The evidence reviewed highlights both the potential and the constraints of *P. palmata* as a feed ingredient. Its balanced amino acid profile, presence of bioactive compounds, and moderate mineral contribution make it a promising partial substitute for conventional proteins. Yet, challenges related to variable composition, fibre-rich cell walls, and risks of mineral or contaminant accumulation limit its current application. Feeding trials generally indicate positive effects on performance, gut health, and product quality, but most are short-term and at limited inclusion levels, making it difficult to define safe upper limits.

To progress from potential to practice, further research should prioritise:

- Establishing safe, effective inclusion ranges through long-term, multi-dose trials in poultry and pigs.
- Optimising processing technologies (blanching, drying, fermentation) to stabilise composition, reduce contaminants, and retain bioactive compounds.
- Assessing nutrient and bioactive transfer into meat and eggs to safeguard food quality and consumer confidence.
- Undertaking life cycle assessments (LCA) to quantify environmental benefits versus conventional feed proteins.
- Evaluating the techno-economic feasibility of large-scale cultivation and processing to support industry adoption.

Addressing these priorities will be essential to unlock the role of *P. palmata* in sustainable poultry and livestock production. With targeted innovation, this underutilised red seaweed could become a valuable component of next generation monogastric feeding strategies.

Author contributions

FK: Conceptualization, Investigation, Methodology, Resources, Writing – original draft, Writing – review & editing. HM: Writing – review & editing. DS: Resources, Validation, Writing – review & editing. PE: Writing – review & editing. MA: Resources, Validation, Writing – review & editing. FS: Writing – review & editing. MS: Writing – review & editing. JH: Funding acquisition, Project administration, Visualization, Writing – review & editing.

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Conflict of interest

Authors DS, PE, and MA were employed by the company Seaweed Generation Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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