Innovative Circular Processing of Red Seaweed for Carrageenan Production and Valorization of Residual Proteins

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Abstract

The transition toward low-carbon food supply chains requires the development of resource-efficient processing technologies capable of maximizing biomass utilization while minimizing environmental impact and material losses. Marine macroalgae represent a strategic climate-smart resource due to their rapid growth rates, lack of freshwater and arable land requirements, and potential to provide functional food ingredients with reduced carbon intensity. In this context, Chondracanthus chamissoi ("yuyo"), a red seaweed from the Southeast Pacific, is recognized for its high carrageenan content, a hydrocolloid widely used in the global food industry for its gelling, stabilizing, and thickening properties.

This study evaluates alternative processing pathways for carrageenan extraction from dried and milled C. chamissoi, integrating a low-carbon and circular bioeconomy perspective. The objectives were: (i) to compare different extraction treatments to optimize carrageenan yield and quality; (ii) to characterize the physicochemical and rheological properties of the extracted hydrocolloid; and (iii) to assess the valorization potential of the residual solid fraction within an integrated seaweed biorefinery framework.

Three extraction methods were assessed: (1) hot water extraction at 60 °C, (2) ultrasound-assisted water extraction, and (3) alkaline extraction using 6% potassium hydroxide (KOH). Key performance indicators included extraction yield, soluble solids content (°Brix), apparent viscosity (0.1% solution at 20 °C), torque, and residual biomass percentage. Protein content in soluble fractions and residual solids was also analyzed to evaluate downstream valorization opportunities.

Preliminary enzymatic hydrolysis trials using proteases and cellulases were conducted to isolate protein fractions from the post-extraction residue. However, effective protein separation and hydrolyzed fraction recovery were not achieved under the tested conditions, primarily due to the persistence of carrageenan-associated matrix structures. As a result, the technological focus was reoriented toward optimizing high-quality carrageenan production while defining selective protein extraction as a medium-term research objective within a broader circular processing strategy.

Among the evaluated treatments, alkaline extraction (6% KOH) achieved the highest carrageenan yield (62.2% of dry biomass), significantly outperforming hot water extraction (43.5%) and ultrasound-assisted extraction (17.5%). The enhanced recovery under alkaline conditions can be attributed to the disruption of sulfate ester bonds and improved release of polysaccharides bound within the structural matrix. However, this method also resulted in higher soluble solids (°Brix = 8.1), indicating greater co-extraction of salts and increased downstream purification requirements.

Hot water extraction at 60 °C demonstrated intermediate yield but superior rheological performance, with the highest apparent viscosity (22.6 cP), suggesting better preservation of molecular weight and sulfation patterns. In contrast, alkaline-extracted carrageenan showed reduced viscosity (7.9 cP), likely due to partial depolymerization effects, while ultrasound-assisted extraction resulted in the lowest viscosity (4.7 cP) and structural degradation, possibly associated with cavitation-induced chain scission.

The residual biomass fraction ranged from 23.6% to 38.2% depending on treatment and retained measurable protein content (2.4–3.7%), with no significant differences across extraction methods. Rather than being discarded, this residual material was milled into seaweed flour and evaluated as an ingredient for plant-based bakery and pastry formulations. Prototype products incorporating residual seaweed flour demonstrated technological feasibility and contributed dietary fiber, marine-derived micronutrients, and functional compounds. This application provides an immediate low-carbon valorization pathway, reducing organic waste generation and extending biomass utilization within the food supply chain.

From a supply chain perspective, integrating carrageenan extraction with downstream utilization of residual biomass supports a circular processing model that enhances material efficiency, reduces waste streams, and diversifies product portfolios. Hot water extraction emerges as a promising lower-impact alternative due to its moderate energy requirements, balanced yield, and superior functional quality, potentially reducing post-processing intensity. While alkaline extraction maximizes hydrocolloid recovery, further optimization of reagent use and effluent management would be required to improve environmental performance.

This research contributes technical evidence toward the development of an integrated seaweed biorefinery model aligned with low-carbon food supply chain objectives. By combining optimized hydrocolloid extraction with incorporation of residual biomass into plant-based food products, the proposed approach enhances resource efficiency, supports circular bioeconomy strategies, and strengthens climate-resilient marine value chains.

The advancement of integrated seaweed processing platforms such as the one proposed here offers significant opportunities for Asia-Pacific collaboration, knowledge exchange, and technology transfer, while informing evidence-based policy frameworks that promote low-carbon marine value chains, sustainable bioindustrial innovation, and climate-resilient food systems across the region.

Keywords:

Chondracanthus chamissoi, carrageenan extraction, low-carbon processing, seaweed biorefinery