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Research Article

High-Pressure Pre-Treatment of *Kappaphycus alvarezii*: Effect of Drying Rate on Physicochemical Properties and Antioxidant Activities

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ABSTRACT

This study focuses on High-Pressure Pre-Treatment to enhance the seaweed's nutritional value and antioxidant potential, which is highly relevant and aligns with the demand for improved food processing techniques that preserve bioactive compounds. High-Pressure Processing (HPP) was applied at varying levels (0, 200, 400, and 600 MPa) to assess its impact on drying efficiency, physicochemical properties, and antioxidant activities. High-Pressure Processing (HPP) at 200 MPa, 400 MPa, and 600 MPa enhanced the drying performance and antioxidant properties of *Kappaphycus alvarezii*. The 600 MPa treatment achieved the fastest drying rate and the highest antioxidant capacity, thereby enhancing the seaweed's functional properties. Moreover, the 600 MPa treatment yielded the highest total phenolic content (50.68±1.51 mg GAE/100 g) and a significant enhancement in total flavonoid content (5.54±0.29 mg QE/100 g). These compounds are crucial for neutralizing free radicals and mitigating oxidative stress. Furthermore, the 600 MPa treatment demonstrated a significant increase in ferric reducing antioxidant power assay (44.58±2.56 mg FeSO4/100 g) and 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging activity (18.86±0.66%) relative to the untreated sample, highlighting the improved antioxidant potential associated with high-pressure treatment. These findings indicate that HPP not only preserves but also enhances the antioxidant properties of *Kappaphycus alvarezii*, which are vital for its health benefits. Additionally, color analysis revealed significant changes in the lightness and chromaticity of the seaweed post-treatment, suggesting improvements in its visual appeal. This research underscores the capability of HPP technology to improve the drying efficiency of *Kappaphycus alvarezii*, thereby boosting its antioxidative properties, marketability, and versatility in various applications.

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INTRODUCTION

Seaweed, particularly *Kappaphycus alvarezii*, is widely recognized for its rich nutritional profile, including polysaccharides, proteins, minerals, vitamins, and phenolic compounds (Princestasari & Amalia 2015; Healy *et al.* 2023). This red seaweed, recognized for its high carrageenan content, has become economically important in sectors like pharmaceuticals, cosmetics, and food (Rupert *et al.* 2022). *Kappaphycus alvarezii* is particularly valued for its high content of carrageenan, a polysaccharide commonly employed as a thickener and gelling agent. In regions like Malaysia, *Kappaphycus alvarezii* plays a critical role in local economies and food security.

Drying process is crucial not only for the quality and shelf life of seaweed but also for its nutritional value (Santhoshkumar *et al.* 2023).

Traditional drying techniques, like open sun drying, are often time-intensive and can result in the degradation of the seaweed's physicochemical properties and bioactive compounds. Recent advancements in non-thermal food processing technologies have introduced high-pressure pre-treatment as a promising method to enhance drying efficiency while preserving the nutritional and functional qualities of seaweed. By employing high-pressure pre-treatment, this research aims to enhance the antioxidant properties of *Kappaphycus alvarezii*, thereby providing a functional food option that can help address the nutritional deficiencies related to antioxidant intake in the population.

High-Pressure Processing (HPP) is an innovative non-thermal method that offers potential for improving food processing by preserving the structural integrity of heat-sensitive compounds and enhancing extraction efficiency (Xi 2017; Tapia-Salazar *et al.* 2019). High-Pressure Processing (HPP) applies isostatic pressure to food materials, which can disrupt the cellular structure, enhance mass transfer, and improve drying rates (Pérez-Lamela *et al.* 2021; Hidangmayum *et al.* 2023). Additionally, HPP has been shown to improve the antioxidant properties of plant materials, which are crucial for neutralizing oxidative stress and promoting health benefits (Pérez-Lamela *et al.* 2021).

The main aim of this study was to assess the impact of high-pressure processing on the antioxidant characteristics of *Kappaphycus alvarezii*, addressing the growing concern of antioxidant deficiencies in the population, which can lead to various health issues such as diabetes, oxidative stress, and chronic diseases. This study examined the effects of HPP at varying pressure levels (0 MPa, 200 MPa, 400 MPa, and 600 MPa) influenced the drying rate, physicochemical attributes, and antioxidant potential of *Kappaphycus alvarezii*. By tackling the existing challenges in preserving bioactive compounds during drying, this research aids in advancing eco-friendly food processing methods that improve the nutritional value and industrial significance of *Kappaphycus alvarezii*.

METHODS

Design, location, and time

The research was carried out at the Functional Food Laboratory and Nutrition Laboratory, situated on the Health Campus of Universiti Sains Malaysia (USM) in Kelantan, Malaysia. The study was conducted between May and August 2024.

Materials and tools

The primary material for this research was the red seaweed *Kappaphycus alvarezii*, collected from Pulau Langkawi, Kedah, Malaysia, in June 2024. The samples were meticulously cleaned with freshwater to eliminate debris, epiphytes, salts, and other impurities from the seaweed's surface. Ferric chloride hexahydrate (FeCl3•6H2O) was sourced from Bendosen, Norway. The compound 2,4,6-Tris(2-pyridyl)-s-triazine (TPTZ) was procured from Fluka, USA, while methanol was obtained from HmbG Chemicals, Germany. Sodium nitrite, acetic acid, sodium acetate trihydrate hydrochloric acid, iron (II) sulphate (Fe2SO4), Folin–Ciocalteu reagent, aluminium chloride, sodium hydroxide, and sodium carbonate were supplied by R&M Chemicals, United Kingdom. Additionally, 2,2-diphenyl-1-picrylhydrazyl (DPPH) and quercetin standards were obtained from Sigma-Aldrich, Germany. All reagents used in this study were of analytical-grade quality.

Procedure

High pressure treatment of seaweed. High-pressure treatments of the seaweed were conducted using equipment from Hiperbaric 55, Spain. The seaweed was sealed in vacuum-packed nylon plastic, placed in containers inside a high-pressure chamber, and processed under controlled conditions of 0 MPa, 200 MPa, 400 MPa, and 600 MPa for 10 minutes at 24°C.

Determination of moisture content. The moisture content of the seaweed samples was evaluated using the AOAC method. The samples were oven-dried at 100±2°C for 24 hours to determine their bone-dry moisture content. Each sample's moisture measurement was repeated in triplicate to ensure accuracy.

Drying rate of seaweed. Oven drying was conducted at 60 °C to determine the drying rate using a Memmert UFE 600. Firstly, 400 g of fresh seaweeds were placed on a tray. The samples' weight was checked hourly until reaching a constant dried weight. The dried seaweed was then ground and packed in zip-lock bags to maintain moisture and stored in a cooler for color analysis and antioxidant analysis. The experimentally

obtained data for the four pressure levels studied (0, 200, 400, and 600 MPa) were represented as a plot of the dimensionless Moisture Ratio (MR) against time:

$$MR = \frac{W - We}{W0 - We}$$

Where W represents the moisture content at any given time t, We is the equilibrium moisture content, and W0 denotes the initial moisture content, all expressed in grams of water per gram of dry solids.

Colour analysis. The colour analysis of fresh seaweed treated with high pressure was conducted using a DS-700 Bumificient colorimeter to measure lightness (L*), redness (a*), and yellowness (b*).

Sample extraction. A sample of 1 g was extracted using 10 mL of 80% methanol at room temperature for 1 hour, followed by vortexing. The extract was centrifuged at 1,400 rpm for 10 minutes, and the supernatant was collected for antioxidant evaluation.

Determination of total phenolic content. The total phenolic content was determined using the Folin-Ciocalteu reagent with minor modifications following the method outlined by Afrin *et al.* (2023). Firstly, 10 µL of the extract was mixed with 10% Folin-Ciocalteu reagent and allowed to react at ambient temperature for 5 minutes. Then, 40 µL of 7.5% sodium carbonate solution was added, and the mixture was left to incubate for one hour. The absorbance was recorded at 765 nm using a microplate reader. A standard curve was created with varying concentrations of gallic acid (Sigma Aldrich, St. Louis, MO, USA), and the results were expressed in terms of Gallic Acid Equivalents (GAE) in mg per 100 g of dried sample.

Determination of total flavonoid content. The Total Flavonoid Content (TFC) was measured using the Aluminum Chloride Colorimetric Assay, with slight adjustments to the method described by Afrin *et al.* (2023). Initially, 11.5 µL of 20% sodium nitrite solution was added to 37.5 µL of the extract and left to react for 6 minutes. Next, 2.5 µL of 8% aluminum chloride solution was added and allowed to incubate for 5 minutes. This was followed by the addition of 7.5 µL of 1 mol/L sodium hydroxide solution, and the mixture was incubated for 15 minutes before recording the absorbance at 510 nm using a microplate reader. A standard curve was created with varying concentrations of calibration curve was established using a quercetin standard. The TFC of the seaweed extract was tested in triplicate and reported as quercetin equivalents (mg QE/100 g).

Ferric reducing antioxidant properties. The FRAP assay was performed using a modified protocol that incorporated the methods from Addai *et al.* (2013) and Chen *et al.* (2018). The FRAP reagent was prepared by combining 300 mM acetate buffer (pH 3.6), 10 mM TPTZ in 40 mM HCl, and 20 mM FeCl3•6H2O in a 10:1:1 ratio. Each 10 µL sample was combined with 200 µL of the prepared FRAP reagent. Following an incubation period of 50 minutes, absorbance was measured at 595 nm. The FRAP value of the seaweed was expressed as FeSO4 equivalents (mg FeSO4/100 g), determined using a calibration curve created with FeSO4 solutions of varying concentrations.

DPPH radical scavenging assay. The seaweed's antioxidant activity was measured using the 1,1-diphenyl-2-picrylhydrazyl (DPPH) assay, based on a modified protocol described by Chen *et al.* (2018). Each sample (150 µL) was mixed with 150 µL of DPPH solution and left to incubate for 45 minutes. Absorbance was recorded at 517 nm. A methanolic DPPH solution served as the control, with methanol acting as the blank reference. The scavenging activity was determined using the formula:

DPPH radical scavenging activity (%)=
(1 - A/B) x 100%

Where A is the absorbance of the sample at 517 nm, and B is the absorbance of the control at 517 nm.

Data analysis

Statistical evaluation was carried out using IBM SPSS Statistics (Version 28) and Microsoft Excel 2013. Results were expressed as means±standard deviation, with significance established at a p-value below 0.05. Variations between means were assessed using one-way ANOVA, followed by Tukey's post-hoc test to identify statistically significant differences.

RESULTS AND DISCUSSION

Effect of pre-treatment on drying characteristics

The current study evaluated the impact of high-pressure treatment on the drying

characteristics of *Kappaphycus alvarezii* seaweed at 60°C, with pressure conditions of 200 MPa, 400 MPa, and 600 MPa compared to a control without pressure treatment. The moisture content was measured hourly over 12 hours to observe the drying kinetics (Figure 1).

The control sample exhibited the greatest initial moisture content, which gradually reduced throughout the drying process. Samples treated at 400 MPa showed a moderately faster rate of moisture reduction, while the 600 MPa treatment resulted in the most rapid initial drying rate compared to the control, particularly during the first 4 hours. This accelerated drying rate at higher pressures suggests that high-pressure processing disrupts the cell structure (Giannoglou *et al.* 2018), facilitating enhanced moisture migration and potentially leading to reduced processing costs (Giannoglou *et al.* 2022). On the other hand, the sample treated at 200 MPa demonstrated the slowest drying rate, likely due to limited structural disruption at moderate pressure (Zhang *et al.* 2020). At this level, the cellular framework may resist deformation, resulting in slower water diffusion compared to the control sample without treatment and those exposed to higher pressure conditions.

The enhanced drying rate under high-pressure conditions can be attributed to several factors. Primarily, the mechanical disruption of the seaweed's cellular structure under high pressure increases the permeability of cell membranes, facilitating moisture release and resulting in faster drying rates (Hidangmayum *et al.* 2023). Additionally, a high temperature of 60°C was employed, which further contributes to rapid drying times (Ali *et al.* 2017). Applying pressures between 400 MPa and 600 MPa can substantially shorten the drying time for *Kappaphycus alvarezii*, thereby enhancing processing efficiency. This reduction in drying time may translate to lower energy costs and higher throughput in commercial seaweed drying operations. The interplay between pressure and temperature in influencing moisture migration requires further exploration, particularly for drying heat-sensitive materials, to enhance industrial applications.

Colour analysis of fresh seaweed and dried powder seaweed

The colour analysis of fresh and dried *Kappaphycus alvarezii* seaweed subjected to various high-pressure treatments (0, 200, 400, and 600 MPa) reveals significant differences in the lightness (L*), redness/greenness (a*), and yellowness/blueness (b*) parameters. Table 1 indicates the colour analysis on the fresh seaweed treated with various high-pressure treatments. The lightness (L*) values of fresh seaweed remain relatively high across all treatments, indicating minimal change in overall brightness. However, the application of 400 MPa and 600 MPa slightly reduces L* values compared to the control, suggesting a slight darkening effect. The L* values for the 400 MPa and 600 MPa treatments with 91.25±0.23 and 91.09±0.04, respectively, were significantly lower than the control and 200 MPa treatment, indicating a noticeable darkening of the seaweed.

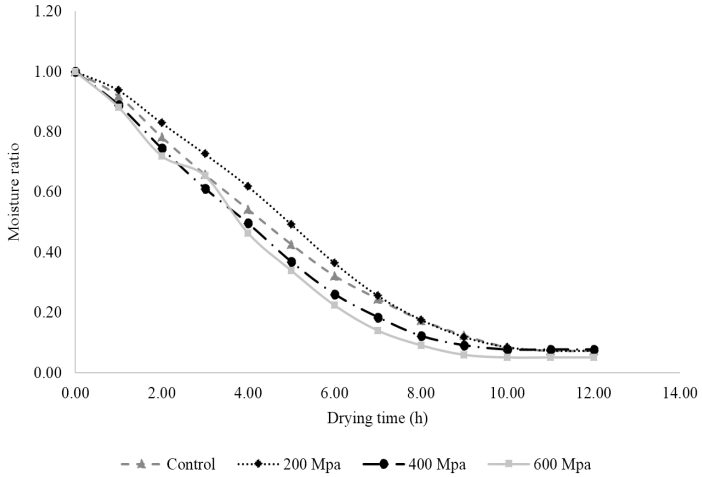

Figure 1. The effect of high-pressure treatment on moisture ratio during drying

The a* values, which indicate redness or greenness, show that all treatments yield a negative a* value, confirming the seaweed's tendency towards a greenish hue. Notably, the 600 MPa treatment leads to a marked enhancement in the greenness of the seaweed, with the a* value decreasing to -1.43±0.02. The b* values, representing the yellow-blue spectrum, decrease with increasing pressure. The control and 200 MPa treatments have similar b* values, indicating a slight yellowish hue. However, the 600 MPa treatment leads to a significant shift towards a bluer hue, as evidenced by the b* value of -3.19±0.05. Nevertheless, the colour differences between treatments were found to be minimal, likely attributed to natural variations in the biomaterial and the influence of residual water content remaining after rinsing (Jönsson *et al.* 2023).

Table 2 presents the colour analysis of dried ground seaweed treated with high-pressure treatment, which is particularly important due to its commercial value and enhanced shelf-life stability. The L* values indicate that the drying process results in a general decrease in lightness if compared to the fresh sample, with the 600 MPa treatment slightly increasing L* to 73.78, suggesting that higher pressure treatments might help in retaining some brightness in the dried product (Raja *et al.* 2019).

The a* values of dried seaweed shift towards the red end of the spectrum, with the highest a* value observed in the 400 MPa treatment (5.09±0.02), indicating an increased red hue compared to the control. The decrease in the a* value to 3.63±0.01 for the 600 MPa sample can be linked to the degradation of pigments, including chlorophylls, carotenoids, and particularly phycoerythrin, the primary light-harvesting pigment in red algae. This degradation is likely due to structural damage to the tonoplast, plasmalemma, and chloroplast membrane during the drying process (Fernández-Rojas *et al.* 2014; Moreira *et al.* 2016).

The b* values show notable variations, with the 600 MPa treatment resulting in the highest b* value (6.94±0.02), signifying a more pronounced yellow hue compared to the control. This could be attributed to the concentration of residual pigments or the generation of browning

Table 1. Colour characteristics of fresh seaweed tretaed with high-pressure pre-treatment

High pressure treatment (MPa)	L*	a*	b*
Control (0)	91.90 ± 0.52^{b}	-1.28 ± 0.06^{b}	-2.39 ± 0.34^{b}
200	91.99 ± 0.23^{b}	-1.30 ± 0.07^{b}	-2.36 ± 0.20^{b}
400	91.25 ± 0.23^{a}	-1.23 ± 0.06^{b}	-2.97 ± 0.12^{a}
600	91.09 ± 0.04^{a}	-1.43 ± 0.02^{a}	-3.19 ± 0.05^{a}

Values are presented as Mean±SD ($n=^{3}$) with different superscript letter, indicate significant difference ($p<^{0.05}$); L*: Indicates lightness (^{0}=black, ^{100}=white); a*: Represents the red-green axis (positive=redness, negative=greenness); b*: Represents the yellow-blue axis (positive=yellowness, negative=blueness); SD: Standard Deviation; MPa: Megapascal

Table 2. Colour characteristics of dried ground seaweed treated with high-pressure pre-treatment

High pressure treatment (MPa)	L*	a*	b*
Control (0)	73.34 ± 0.37^{b}	3.19 ± 0.42^{a}	5.80 ± 0.30^{c}
200	72.80 ± 0.25^{a}	4.38 ± 0.02^{c}	4.15±0.01a
400	72.92 ± 0.02^{a}	5.09 ± 0.02^{d}	4.92 ± 0.02^{b}
600	73.78 ± 0.02^{c}	3.63 ± 0.01^{b}	6.94 ± 0.02^{d}

Values are presented as Mean±SD ($n=^{3}$) with different superscript letter, indicate significant difference ($p<^{0.05}$); L* indicates lightness (^{0}=black, ^{100}=white); a* represents the red-green axis (positive=redness, negative=greenness); b* represents the yellow-blue axis (positive=yellowness, negative=blueness); SD: Standard Deviation; MPa: Megapascal

compounds during the drying process. The increased yellowness of the sample may be due to the dominance of carotenoids over chlorophylls after drying and/or the effects of Maillard reactions (Moreira *et al.* 2016).

Total flavonoid content and total phenolic content of high-pressure treated seaweed

Seaweed extracts are rich in antioxidants, with various seaweed species generating unique types of antioxidant compounds (Corsetto *et al.* 2020). Polyphenols are recognized for their versatile antioxidant properties, primarily due to their phenolic structure, which enables them to act as electron traps and neutralize peroxide, hydroxyl radicals, and superoxide anions (Kindleysides *et al.* 2012).

The Total Phenolic Content (TPC) at 200 MPa shows a slightly reduced but comparable value to the control, likely due to the degradation of sensitive flavonoid compounds under moderate pressure. Conversely, at 400 MPa, the TPC nearly matches control levels, suggesting partial recovery or improved extraction efficiency at this pressure. Remarkably, the 600 MPa treatment significantly enhances TPC to 50.68 mg GAE/100 g, indicating that high pressure promotes the release or preservation of flavonoids. High-pressure treatment at 600 MPa led to a substantial increase in total phenolic content, aligning with the research goal of identifying processing methods that boost bioactive compounds in *Kappaphycus alvarezii*, thereby improving its potential as a dietary antioxidant source. Garcia-Vaquero *et al.* (2021) successfully produced extracts with high yields of Total Phenolic Content (TPC), Total Phlorotannin Content (TPhC), Total Flavonoid Content (TFC), and Total Tannin Content (TTC). Variations in TPC were attributed to differences in HPP settings, treatment parameters, and seaweed species. Similar results were reported by Suwal *et al.* (2019), where HPP application increased polyphenol release from *Solieria chordalis* but not from *Palmaria palmata.*

Total Flavonoid Content (TFC) increases with pressure, reaching the highest values at 400 MPa (5.81±0.13 mg QE/100 g) and 600 MPa (5.54±0.29 mg QE/100 g) (Table 3). The significant increase in TFC under these conditions suggests that high-pressure treatment not only enhances the release of bound flavonoids from the cellular matrix but may also facilitate the biosynthesis of secondary metabolites, such as phenolic compounds. This observation is consistent with the findings of Fernández-Jalao *et al.* (2019), who reported that applying 600 MPa significantly enhanced the Total Phenolic Content (TPC) in 'Granny Smith' apple purée. The authors attributed this increase to cellular disruption induced by high-pressure processing, which enhances the extraction efficiency of bioactive compounds.

Antioxidant activity assessment using Ferric Reducing Antioxidant Power (FRAP) and 2,2-diphenyl-1-picrylhydrazyl (DPPH) scavenging activity

The antioxidant activity of *Kappaphycus alvarezii* was assessed using FRAP and DPPH assays to examine the impact of high-pressure treatment on its antioxidative potential. Table 4 demonstrates that as the applied pressure increased from 0 MPa (control) to 600 MPa, both FRAP values and DPPH radical scavenging activities showed a significant improvement.

The FRAP assay measures the seaweed's ability to reduce ferric ions, reflecting its total antioxidant capacity. The results showed a notable increase from 26.09±2.21 mg FeSO4/100 g (control) to 44.58±2.56 mg FeSO4/100 g at 600 MPa, indicating enhanced redox activity under high-pressure treatments (Table 4). This enhancement aligns with the findings of Suwal *et al.* (2019), where high-pressure processing facilitated the extraction of polyphenols, key contributors to the antioxidant activity of red macroalgae. The observed increase is likely due to the disruption of cell structures, which facilitates the release of bound antioxidant compounds such as polyphenols and flavonoids during the extraction process (Garcia-Vaquero *et al.* 2021).

The DPPH radical scavenging assay, on the other hand, quantifies the seaweed's capacity to neutralize free radicals. The control sample exhibits the lowest DPPH scavenging activity (14.19±1.35%), indicating a baseline level of antioxidant capacity. As pressure increases, the scavenging activity also increases, with the 600 MPa treatment showing the highest activity at 18.86±0.66%. A study by Garcia-Vaquero *et al.* (2021) found that a 2,2-diphenyl-1-picrylhydrazyl (DPPH) assay on HPP-treated seaweeds revealed higher radical scavenging activity.

Seaweeds thrive in challenging environmental conditions, including rapid temperature fluctuations, osmotic pressure,

Table 3. Total flavonoid content and total phenolic content of seaweed pre-treated with high pressure

High pressure treatment (MPa)	Total phenolic content (mg GAE/100 g)	Total flavonoid content (mg QE/100 g)
Control (0)	42.22±0.53[b]	2.70±0.16[a]
200	36.00±1.95[a]	4.64±0.23[b]
400	41.27±2.40[b]	5.81±0.13[c]
600	50.68±1.51[c]	5.54±0.29[c]

Values are presented as Mean±SD (n=[3]) with different superscript letter, indicate significant difference (p<[0.05]); SD: Standard Deviation; MPa: Megapascal; mg GAE/g: milligrams of Gallic Acid Equivalents per [100] gram; mg QE/100 g: milligrams of Quercetin Equivalent per [100] gram

Table 4. Antioxidant capacity of *Kappaphycus alvarezii* as determined with FRAP and DPPH radical scavenging activity methods

High pressure treatment (MPa)	FRAP (mg FeSO4/100 g)	DPPH radical scavenging activity (%)
Control (0)	26.09±2.21[a]	14.19±1.35[a]
200	33.78±2.78[b]	15.97±1.52[ab]
400	44.29±1.95[c]	16.94±0.84[ab]
600	44.58±2.5[6c]	18.86±0.66[b]

Values are presented as Mean±SD (n=[3]) with different superscript letter, indicate significant difference (p<[0.05]); SD: Standard Deviation; DPPH: [2],[2]-diphenyl-[1]-picrylhydrazyl; MPa: Megapascal; FRAP: Ferric Reducing Antioxidant Power; mg FeSO[4]/g: milligrams of Ferrous Sulfate per [100] gram

varying light levels, and periods of desiccation. These factors induce the production of free radicals and robust oxidizing mediators (Afrin *et al.* 2023). This enhancement in antioxidant activity could be directly linked to the increased TPC and TFC observed under high-pressure treatments, as these compounds contribute significantly to the seaweed's ability to neutralize free radicals.

Kappaphycus alvarezii is a large tropical red macroalga that can grow up to two meters in length (Jalal *et al.* 2023) and is known for its rapid growth rate, making it highly suitable for use in the food and pharmaceutical industries (Mohammad *et al.* 2019). This species contains phycoerythrin, a protein-pigment complex, along with chlorophyll and carotenoid complexes, which contribute to its distinctive colouration (Rudke *et al.* 2020). Additionally, *Kappaphycus alvarezii* has been shown to contain various bioactive compounds, including alkaloids, carotenoids, amino acids, flavonoids phytosterols, phenolics, terpenoids, phlorotannins, and tannins, all of which have demonstrated efficacy in inhibiting DPPH activity (Jalal *et al.* 2023). The polyphenolic compounds in this seaweed serve as a valuable source of antioxidants, offering protective and beneficial effects for human health.

CONCLUSION

This study demonstrates that high-pressure pre-treatment is an effective method for enhancing the drying rate and significantly improving the antioxidant properties of *Kappaphycus alvarezii*. The 600 MPa high-pressure pre-treatment significantly increased the total phenolic content (50.68±1.51 mg GAE/100 g), total flavonoid content (5.54±0.29 mg QE/100 g), FRAP (44.58±2.56 mg FeSO4/100g) and DPPH scavenging activity (18.86±0.66%) compared to the control (0 MPa). Additionally, it reduced drying time by accelerating moisture migration during the initial phases of drying. These enhancements underscore the potential of high-pressure processing to improve the nutritional

and functional properties of *Kappaphycus alvarezii*. The significant reduction in drying time achieved through high-pressure processing not only enhances the efficiency of processing *Kappaphycus alvarezii* but also supports our research objective of optimizing food processing methods to retain and enhance nutritional quality. These enhancements have important implications for public health, as incorporating this seaweed into diets could help combat oxidative stress and related health issues. Future research is recommended to explore the combined effects of high pressure and varying temperatures on moisture migration, which could offer greater insights into optimizing drying processes for heat-sensitive materials. Future studies should consider the economic implications of implementing high-pressure technology in commercial settings, assessing cost-benefit ratios and scalability. By addressing these areas, the seaweed industry can enhance its sustainability and profitability while delivering high-quality products to consumers that promotes health benefits.

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DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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