Impact of ultrasonic-assisted extraction period on physical properties of ulvan

Suci Istiqlaal[1], *Sukarno*[1], *Uju*[2,3], *Azis* Boing Sitanggang[1] and *Christofora* Hanny Wijaya[1*]

[1]Department of Food Science and Technology, Faculty of Agricultural Engineering and Technology, IPB University, Bogor, 16680. Indonesia
[2]Department of Aquatic Product Technology, Faculty of Fisheries and Marine Science, IPB University, Bogor, 16680, Indonesia
[3]Surfactant and Bioenergy Research Center (SBRC), IPB University, Bogor, 16127, Indonesia

Abstract. Ulvan, a sulfated polysaccharide derived from *Ulva* sp., has potential as a hydrocolloid owing to its rheological properties, which are crucial for its application as a food additive. However, limited information is available on the effects of the ultrasonic-assisted extraction (UAE) period on the rheological properties of ulvan. This study investigated the impact of different UAE periods on the physical properties of ulvan and analyzed the flow behavior of optimal ulvan solutions at varying concentrations and temperatures. A Randomized Complete Block Design (RCBD) was employed, with the extraction method as the blocking factor and the extraction period as the treatment. The results showed that increasing the UAE duration has significantly improved the extraction efficiency sign and functional properties, with the two-hour treatment yielding the best results. Ulvan exhibited pseudoplastic behavior and shear-thinning properties, which were influenced by both concentration and temperature. These findings highlight the potential of UAE-processed ulvan as a natural hydrocolloid for food applications, particularly for enhancing texture, stability, and water-holding capacity. Its shear-thinning behavior suggests its suitability for use in sauces and dressings. This study underscores the UAE's role in optimizing the hydrocolloid functionality of ulvan for food applications.

1. Introduction

Sulfated polysaccharides from green seaweed, known as ulvans, are potential hydrocolloids for food applications. In the food industry, hydrocolloids are widely employed as gelling, thickening, and stabilizing agents to improve texture [1, 2]. Their functionality is influenced by their physical and chemical properties, which can differ based on the seaweed species and post-harvest processing methods [3], including the extraction techniques applied.

Hot water extraction (HWE) is a commonly used method, but it requires time and energy and offers relatively low extraction efficiency. As extraction technology advances, ultrasound-assisted extraction (UAE) can improve the yield efficiency. Recent studies have demonstrated that UAE enhances cell wall disruption, leading to higher ulvan extraction efficiency in a shorter time than conventional methods. Additionally, UAE helps preserve the key functional properties of ulvan, such as water retention capacity and viscosity, which are crucial for its applications in the food industry.

Despite these advancements, most UAE research has primarily focused on optimizing the yield, while its effects on the structural integrity and functional properties of ulvan remain unexplored. In particular, the relationship between the extraction period and ulvan's hydrocolloid functionality in food applications has not been fully investigated, highlighting the need for further research to maximize ulvan's potential in food formulations.

Based on the thermal power equation, the extraction period is an important factor that requires further investigation [4]. In the ultrasonication process, the thermal energy absorbed by the sample influences the increase in temperature, which can affect the WHC and viscosity. Although UAE has shown potential for improving the efficiency of ulvan extraction, complete information on the effect of the extraction period on the WHC and viscosity of ulvan is not available. According to Kazemi et al., the extraction period affects the viscosity of ulvan, but there is an optimal limit that needs to be determined to avoid damaging the ulvan structure [5].

* Corresponding author: channywijaya@apps.ipb.ac.id

This study aimed to explore the effect of the UAE of ulvan at various periods on the physical properties of ulvan and to analyze the flow behavior of the optimal ulvan solution at different concentrations and temperatures. These findings are expected to provide new insights into determining the optimal extraction period to obtain suitable ulvan properties for several industrial uses.

2. Materials and methods

2.1 Materials and chemicals

Ulva lactuca was obtained from Ujung Genteng, Sukabumi District, West Java, Indonesia. To eliminate impurities, the samples were rinsed thoroughly with fresh water before air-drying in a shaded area for four days. After drying, the samples were finely ground using a disc mill and sieved through an 80-mesh filter. The resulting seaweed powder was stored in vacuum-sealed plastic bags until further analysis.

Analytical grade ethanol (96%) and isopropyl alcohol (IPA) were obtained from Merck (Darmstadt, Germany). The instruments utilized included an ultrasonic cleaner operating at 40 kHz with a power of 120 W (Desen DSA100-SK4.0L, China), FT-IR ATR spectrometer (Bruker ALPHA II-Platinum, Germany), centrifuge (Eppendorf 5810 R, Germany), viscometer (AMETEK Brookfield, USA), and rheometer (Anton Paar MCR 92, Austria; CP diameter: 50 mm; angle: 1°).

2.2 Ulvan extraction

Ulvan extraction followed the Ramadhan et al. method, with certain modifications [6]. Ultrasonic-assisted extraction (UAE) was conducted at 80 °C for 1, 2, and 3 h, referred to as UAE-1, UAE-2, and UAE-3, respectively. As a control, hot water extraction (HWE) was performed under the same temperature conditions for 1, 2, and 3 h, designated as HWE-1, HWE-2, and HWE-3, respectively.

2.3 Parameter measurement

Ulvan yield analyzed by Ramadhan et al., Yuan et al, method used to analyze WHC and OHC, ulvan color analyzed by Inoubli et al., and viscosity measured using a viscometer [6, 7, 8].

2.4 Selection stage of treatments

The Bayesian method is a commonly used algorithm and effectiveness index. This approach is recognized as an effective supervised classification technique because it utilizes datasets from multiple classes to classify an object into a specific category. The Bayesian method has been extensively implemented in various domains, including agriculture and healthcare. By leveraging Bayesian probability, this statistical technique manages data uncertainty using Bayes' theorem, as referenced in [9].

2.5 Rheology measurement

Viscosity and flow curves using the Shao et al. method at 1–1000 s^{-1} [10]. A power-law model was used to analyze the flow properties of ulvan, allowing for a detailed characterization of its rheological behavior.

$$\tau = k\,(\gamma)^n \qquad (1)$$

where τ represents the shear stress, γ denotes the shear rate, k is the consistency index (reflecting the liquid consistency or concentration), and n is the power-law index. The value of n determines the fluid behavior; when $n = 1$, the fluid exhibits Newtonian characteristics, meaning that its viscosity remains constant regardless of the shear conditions. If $n < 1$, the fluid behaves as a pseudoplastic fluid, exhibiting shear-thinning properties. Conversely, when $n > 1$, the fluid exhibits dilatant behavior, where the viscosity increases with the shear rate.

2.5.1 Ulvan of viscosity versus temperature at different concentrations

Viscosity measurements were performed at increasing temperatures from 20 to 90°C using the method described by Shao et al. at 1, 1.5, and 2% concentrations of ulvan solution prepared according to Section 2.5.2 [10].

2.5.2 Ulvan of flow properties at different concentrations

To prepare the ulvan solution, ulvan concentrations of 1, 1.5, and 2% were achieved by dispersing ulvan in deionized water while stirring at 80°C. Next, the sample was poured onto a rheometer for viscosity measurements [10].

2.6 Data analysis

SPSS software (version 25) was used for analysis of variance (ANOVA) of the observed data, followed by Tukey's multiple range test as a post-hoc analysis. Pearson’s product-moment correlation was used to determine the relationship between WHC and ulvan viscosity.

3. Results and discussion

3.1 Yield of ulvan

The findings of this study indicate that the ultrasonic treatment produced comparable results to those obtained using the control method within the same extraction period, with no satistically significant difference between UAE-1 and HWE-3 (Fig.1). This suggests that achieving an equivalent ulvan yield requires three hours of extraction using HWE, whereas UAE can achieve the same result in just one hour. On average, ultrasonic-assisted extraction led to a 14.01% increase in ulvan yield compared to that of the conventional method.

These results align with those of previous research [11], which demonstrated that the use of ultrasonic waves can enhance ulvan extraction efficiency. This improvement was attributed to the cavitation effect generated by ultrasonication, which disrupted the seaweed cell walls, causing more ulvan to be extracted than that in the control. Ultrasonic waves break the hydrogen bonds between cellulose and hemicellulose within the cell wall, generating localized heat and shear stress that improve the solubility and diffusion of polysaccharides. This ultimately resulted in a significant increase in the total extraction yield.

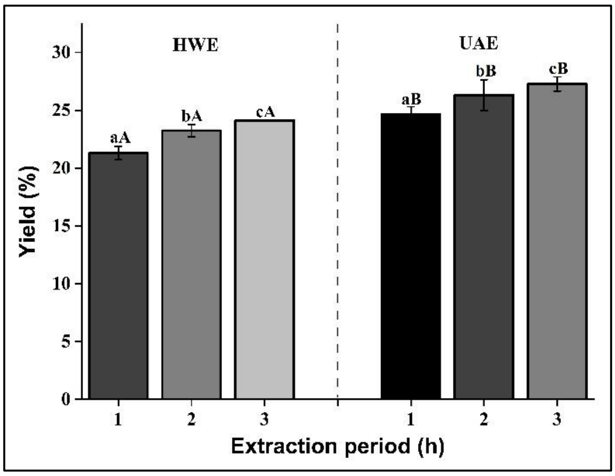

Fig. 1. Effect of extraction period on ulvan yield using HWE and UAE. Different lowercase letters indicate significant differences within the same extraction method across different extraction periods, whereas different uppercase letters indicate significant differences between extraction methods within the same extraction period ($p < 0.05$). Error bars represent standard deviation (n=3).

In this study, we also found that each ultrasonic-assisted extraction period increased ulvan yield by 1.31%. However, extending the extraction time beyond a certain point decreases the efficiency. Ultrasonic waves may improve the extraction efficiency in the short term; however, they become less effective over time. Feng et al. found that the polysaccharide yield improved with extraction time but decreased after a specific duration owing to the limited thermal stability of polysaccharides, resulting in their degradation [12]. Shu et al. found similar results, with polysaccharide output increasing for the first 1-3 hours but decreasing after 4 h of extraction [13].

As seen in Fig.2, the visual appearance of ulvan extracted using UAE appears whiter compared to that obtained through HWE. The L value is significantly different for both methods and periods, with values of 82.00, 80.25, 75.75, 80.75, 72.00, and 70.50, respectively. However, a gradual decrease in brightness was observed as the extraction time increased for both methods. The decrease in the L ulvan value as the extraction time increased can be caused by structural degradation, increased impurity content, and oxidation. Longer extraction times can cause depolymerization of polysaccharides, increase the solubility of compounds such as proteins or pigments, and accelerate oxidation reactions that darken the color. In addition, changes in crystallinity can reduce light scattering, making the ulvan appear darker. The combination of these factors leads to a decrease in the brightness of the ulvan in extractions of longer durations.

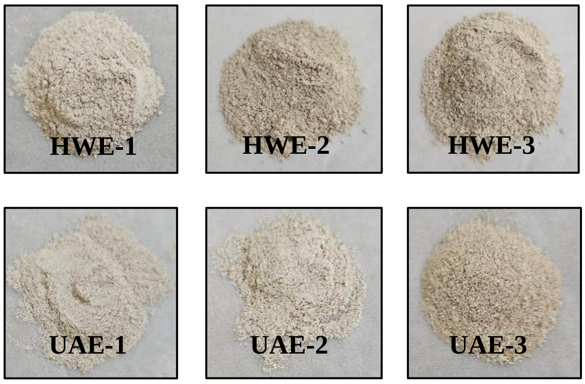

Fig. 2. Visual appearance of ulvan extracted using hot water extraction (HWE) and ultrasound-assisted extraction (UAE).

3.2 Fuctional group of ulvan

FTIR analysis confirmed the presence of characteristic functional groups in ulvan extracted using different methods and durations. Absorption peaks observed within the 500–4000 cm^{-1} range indicate spectral properties typical of polysaccharides [14]. The FTIR spectra of the ulvan samples obtained in this study displayed distinct signals corresponding to the polysaccharide structures. A broad absorption band detected at approximately 3221.79–3275.58 cm^{-1} was attributed to the stretching vibrations of the hydroxyl (-OH) group [15]. All ulvan samples had carboxyl groups attached to uronic acid (C=O) at 1623.19–1643.69 cm^{-1}, while UAE-1, UAE-2, and UAE-3 had peaks at 1416.192, 1422.341, and 1420.291 cm^{-1}, respectively [15, 16]. Sulfate groups were detected at 1050-1213 cm^{-1} [10] in all ulvan samples. UAE-2 and UAE-3 showed absorption bands at 1073-1076 cm^{-1}, which are related to rhamnose [17]. Kazemi et al. detected the distinctive fingerprint region of ulvan in all UAE samples, which ranged from to 848-1200 cm^{-1} [5]. These findings confirm that the sulfated polysaccharide isolated from *Ulva lactuca* is ulvan.

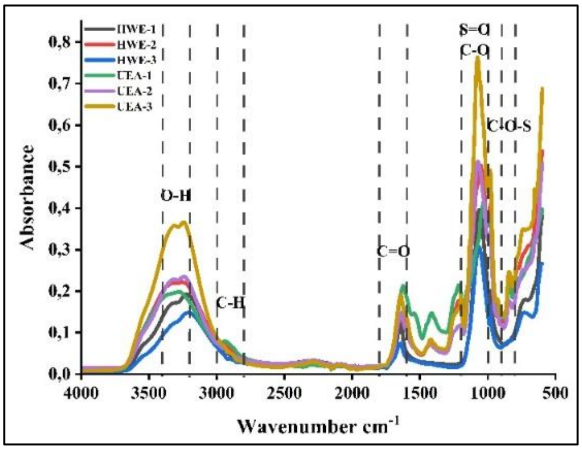

Fig. 3. Ulvan functional groups based on FTIR spectroscopy

3.3 Water holding capacity of ulvan

Water-holding capacity (WHC) refers to the ability of ulvan to retain water, which is measured in grams of water per gram of ulvan [8]. As illustrated in Fig. 4, the UAE method resulted in a greater WHC than HWE, although the difference between HWE-1 and UAE-1 was not statistically significant. The highest WHC value was observed for ulvan extracted using UAE-2 (9.18 g water/g ulvan), while the lowest was found for ulvan extracted using HWE-3 (5.47 g water/g ulvan).

The increased WHC of ulvan obtained via UAE can be related to its structural properties, as demonstrated by the FT-IR spectra in the preceding sections. Stronger absorbance in the 3200-3400 cm^{-1} area suggests more hydroxyl (-OH) exposure, which increases water retention through hydrogen bonding. Sulfate groups (1050-1213 cm^{-1}) were found in all samples, and their intensity can impact WHC due to their hydrophilic nature. Rhamnose (1073-1076 cm^{-1}) in the UAE sample may enhance its hydration characteristics. These data imply that structural variations in UAE-extracted ulvans improve their water retention relative to that of HWE.

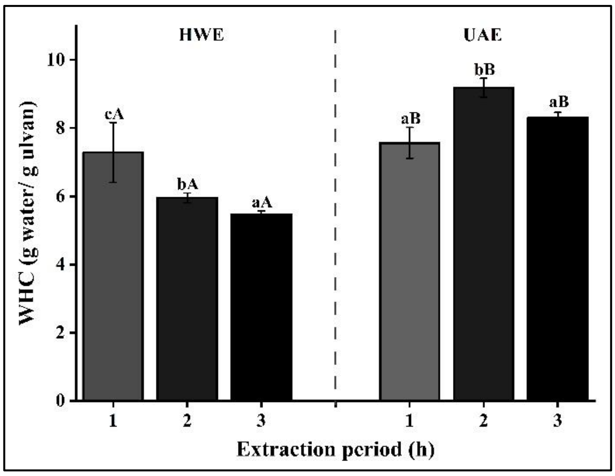

Fig. 4. Ulvan water-holding capacity using different periods and extraction methods. Different lowercase letters indicate significant differences within the same extraction method across different extraction periods, whereas different uppercase letters indicate significant differences between extraction methods within the same extraction period ($p < 0.05$). Error bars represent standard deviation (n=3).

Damage and pore enlargement of seaweed cell walls were observed to be higher in ultrasonic wave-assisted extraction than in conventional extraction (HWE). This effect is attributed to the cavitation mechanism, which generates strong mechanical shear forces that facilitate cell wall disruption. This technique yields ulvan with a larger molecular weight. The WHC of polysaccharide sulfates is correlated with their molecular weights. This may explain the higher WHC of ulvan extracted using ultrasound-assisted extraction compared to that extracted using HWE. However, when the extraction period exceeded 2 h, the water-holding capacity decreased significantly.

This phenomenon was caused by the degradation of ulvan extracted for 3 h. Wu et al. reported that the water-holding capacity of sulfated polysaccharides decreases when they are degraded into smaller components [18]. While the 1h period shows non-optimal results.

3.4 Oil holding capacity of ulvan

The ability of ulvan to store oil is expressed as OHC [8]. As shown in Fig.4, the OHC of ulvan was not significantly different among the treatments. Although Wang et al. stated that treatment reduces particle size and exposes hydrophobic groups in protein compounds, in this study, the OHC value of ulvan was not significantly different between HWE and UAE [19]. This may be due to the low ultrasonic power used in this study (120 W), which is thought to be insufficient to open the hydrophobic groups of ulvan. Ultrasonic power and treatment duration influence the functional properties of the polysaccharides. Ultrasonically assisted extraction at 400 W enhanced the formation of three-dimensional gel structures in legume proteins due to the opening of hydrophobic groups. Moreover, polysaccharides do not have significant hydrophobic properties, such as proteins, because most of their functional groups are hydrophilic (such as hydroxyl groups). Wang et al. reported that ultrasonic treatment enhances the exposure of hydrophilic groups in polymers, making them more accessible to water [20]. This process effectively improves the water solubility of high molecular weight exopolysaccharides.

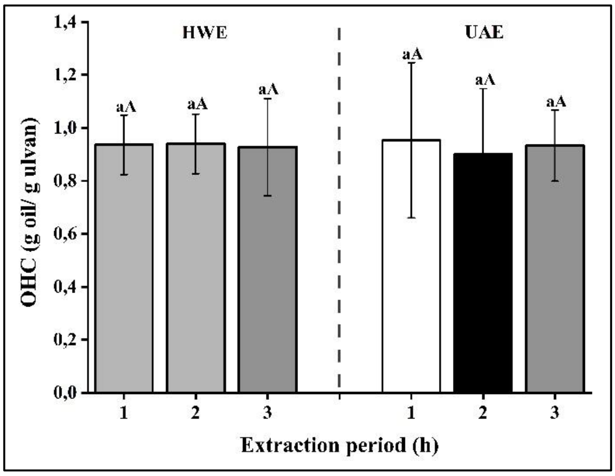

Fig. 5. Ulvan oil-holding capacity using different periods and extraction methods. Different lowercase letters indicate significant differences within the same extraction method across different extraction periods, whereas different uppercase letters indicate significant differences between extraction methods within the same extraction period ($p < 0.05$). Error bars represent standard deviation (n=3).

The oil-holding capacity (OHC) of ulvan was lower than its water-holding capacity (WHC), with values ranging from 0.60–1.40 g oil/ g ulvan. This finding aligns with those of Yang et al. and Gannasin et al., who indicated that hydrocolloids generally exhibit low OHC and are negatively correlated with WHC [21, 22].

3.5 Viscosity of ulvan

The viscosity of ulvan, which ranged from 7.4 to 8.8 cP, was affected by both the extraction method and period. UAE-extracted ulvan had a higher viscosity than HWE, with UAE-2 having the highest value (8.8 cP) and HWE-1 and HWE-3 having the lowest values (7.4 cP). This discrepancy is most likely due to the structural integrity of the ulvan extracted using UAE, as indicated by the FTIR data. The larger absorption bands of the hydroxyl (-OH) and sulfate (S=O) groups in the UAE samples suggest improved hydration, which contributes to an enhanced water-holding capacity (WHC). The link between viscosity and WHC indicates that UAE contributes to the natural structure of ulvan, allowing it to hold more water. However, when the extraction time exceeded 2 h, the viscosity and WHC decreased, probably due to molecular disintegration, as demonstrated by Yu et al. [23]. These findings illustrate the benefits of UAE in preserving the functional qualities of ulvan compared to traditional approaches such as HWE.

In addition, the increase in the viscosity of ulvan during the 2h period is thought to be closely related to its molecular weight. Previous studies have reported a strong positive correlation between the molecular weight and viscosity of hydrocolloids [11]. Extraction for more than 2 h may decrease the molecular weight of ulvan, resulting in a decrease in viscosity.

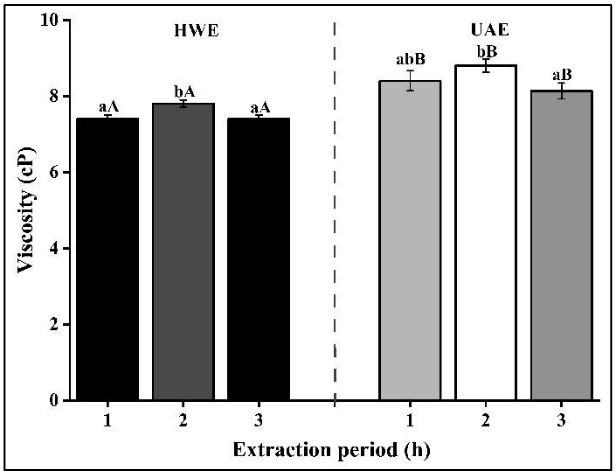

Fig. 6. Ulvan viscosity using different periods and extraction methods. Different lowercase letters indicate significant differences within the same extraction method across different extraction periods, whereas different uppercase letters indicate significant differences between extraction methods within the same extraction period ($p < 0.05$). Error bars represent standard deviation (n=3).

A correlation analysis result of 0.764 between WHC and ulvan viscosity, with a significance level < 0.05 (0.00). The Bayes method was used to select the optimal treatment considering the WHC and viscosity values of ulvan. UAE-2 was identified as the best treatment for further evaluation, as it achieved the highest total score (5.5) from the Bayes calculation (Table 1).

Table 1. Bayesian method-based weighted ranking of treatment groups using WHC and viscosity parameters.

Parameter	Weight		Total Value	Rank
	WHC	Viscosity		
	0.5	0.5		
	Rank			
HWE-1	3	1	2	3
HWE-2	2	2	2	3
HWE-3	1	1	1	4
UAE-1	4	4	4	2
UAE-2	6	5	5.5	1
UAE-3	5	3	4	2

3.6 Viscosity of ulvan at different concentrations and temperatures

The relationship between temperature and the viscosity of the ulvan solutions is illustrated in Fig. 7. The results indicated an inverse correlation, where an increase in temperature led to a reduction in viscosity. This pattern is consistent with that of previous studies on polysaccharides, which have shown that viscosity is affected by parameters such as shear rate, temperature, pressure, and shear duration [24]. As explained by López-Barraza et al., higher temperatures lead to an increase in molecular kinetic energy, thereby enhancing molecular movement [16]. This increased activity weakens the intermolecular interactions, ultimately reducing the viscosity of ulvan.

This phenomenon is consistent with the Arrhenius equation [15], which asserts that the viscosity of a fluid decreases as the temperature increases owing to the decrease in flow resistance. This mechanism is comparable to that of other hydrocolloids, such as pectin and carrageenan, which lose viscosity as the temperature increases owing to the weakening of intra- and intermolecular interactions.

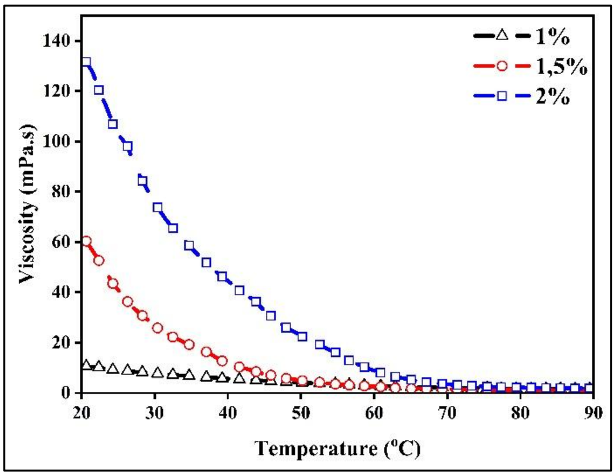

Fig. 7. Viscosity of ulvan at different concentrations and temperatures.

Additionally, the influence of temperature on the viscosity characteristics of ulvan solutions is highly dependent on the concentration. Ulvan solutions exhibited greater sensitivity to temperature fluctuations at higher concentrations. This phenomenon is likely attributed to the weakening of intermolecular forces as the temperature increases, leading to molecular disentanglement and a subsequent reduction in the viscosity [24]. The more pronounced viscosity decline at higher concentrations suggests that molecular interactions play a dominant role in these solutions, making them more susceptible to temperature changes.

In contrast, at lower concentrations (0.5%), ulvan solutions displayed flow properties akin to Newtonian fluids, where viscosity remained relatively stable regardless of changes in shear rate. In Newtonian fluids, the viscosity is constant under specific temperature and pressure conditions and is unaffected by shear stress. Under these circumstances, the limited number of ulvan molecules dispersed in the solvent resulted in weaker cohesive forces between the polymer chains. Consequently, the viscosity of the solution is influenced more by the intrinsic properties of the solvent than by the macromolecular structure of ulvan.

Furthermore, at lower concentrations, the formation of complex molecular networks, which typically arise at higher concentrations owing to hydrogen bonding and electrostatic interactions, is significantly reduced. The viscosity remained relatively unchanged across different shear rates, which is a defining characteristic of Newtonian fluids. At lower concentrations, temperature has a diminished effect on viscosity because the polymer structure does not undergo substantial alterations that could impact flow behavior. However, at higher concentrations, elevated temperatures weakened the intermolecular interactions, leading to a more significant decline in viscosity. This behavior indicates that at lower concentrations, ulvan is more uniformly dispersed in water, preventing the formation of intricate macromolecular structures and resulting in more stable flow properties that resemble those of Newtonian fluids.

3.7 Ulvan flow properties at different concentrations

The flow characteristics of the ulvan solutions were evaluated using the power-law model (Eq. (1)), and the results are summarized in Table 2. The model exhibited a coefficient of determination (R^2) of 1 across all samples, signifying an excellent fit and the absence of yield stress (τ_o). The flow behavior index (n), which signifies the degree of shear-thinning behavior, was below 1, ranging from 0.98 to 0.99. These values confirmed the pseudoplastic nature of all the samples. The shear-thinning properties observed in ulvan solutions are likely due to the disruption of intermolecular entanglements among polymer chains during shear application, as previously described by Seo et al. [25]. Similar findings have been reported by Wu et al. [26]. Furthermore, as the concentration of ulvan increased, the molecular mobility within the solution became more restricted, while the crosslinking interactions were enhanced, leading to a more pronounced pseudoplastic behavior.

Table 2. Flow behavior parameters of ulvan solutions at different concentrations.

	1%	1.5%	2%
r^2	1	1	1
n	0.99	0.98	0.98
k	0.002	0.004	0.006
μ_{10} (mPa.s)	2.88	4.06	6.19
μ_{50} (mPa.s)	2.74	4.05	6.08
μ_{1000} (mPa.s)	2.66	3.72	5.57

The ulvan solutions in this study displayed pseudoplastic behavior, which is consistent with the findings of earlier research [17]. This property was effectively represented by the power-law model, as indicated by the flow behavior index (n) being less than 1.0, confirming the shear-thinning characteristics of ulvan (Table 2). As the ulvan concentration increased, the consistency coefficient (k) showed an upward trend from 0.0029 to 0.0064, whereas the n value declined. These variations suggest a greater deviation from Newtonian flow, indicating a stronger pseudoplastic behavior at higher concentrations. In line with Marcotte *et al.*, a decrease in the flow behavior index (n) indicated an increase in pseudoplasticity for all hydrocolloids at increasing concentrations [27]. The consistency coefficient (k) increased as predicted with increasing hydrocolloid content.

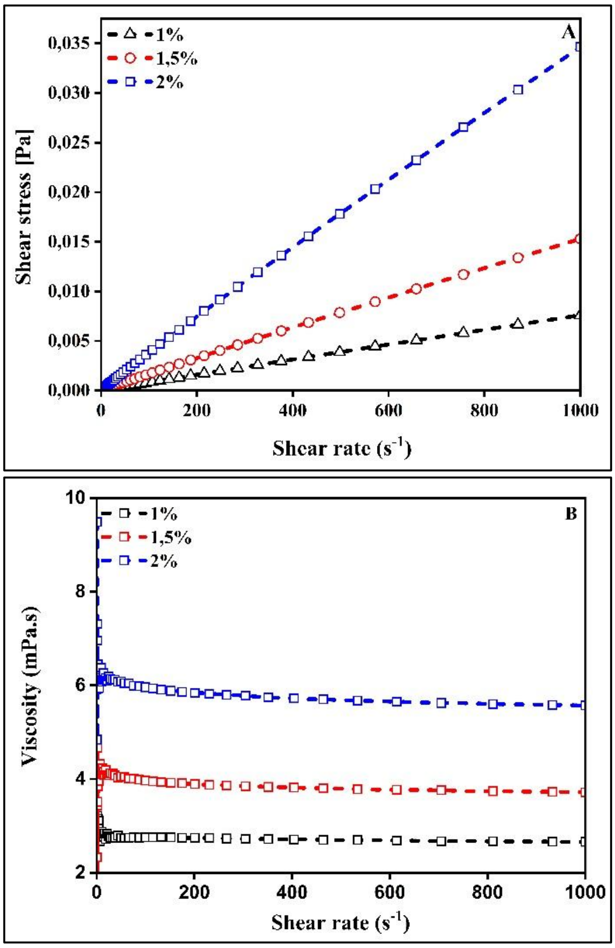

Fig. 8. Flow behaviour of ulvan solution at different concentrations: (A) shear stress and (B) apparent viscosity.

Ulvan concentration significantly affects viscosity. In dilute aqueous solutions, where molecular interactions are minimal, the viscosity increases gradually with concentration, as reflected in the slow rise in k values from 0.0029 to 0.0064. However, once the concentration reaches a critical threshold, where molecules begin to interact, the viscosity exhibits a noticeable shift. Beyond this point, the rate of increase in viscosity becomes more pronounced owing to the formation of molecular entanglements, which leads to stronger intermolecular interactions [24]. At low concentrations, ulvan forms little tissue; therefore, the resistance to fluid flow is insignificant. Under these conditions, the properties of ulvan tend to remain Newtonian, where the viscosity is constant and independent of the shear rate.

However, at higher concentrations, more tissue was formed than at lower concentrations. At low shear rates, the viscosity is high because the network remains intact and offers resistance to the flow. However, when a higher shear rate is applied, these networks can deform or even bond back, causing a change in the flow properties. If these networks deform, the flow becomes pseudoplastic, and the viscosity decreases as the shear rate increases. This phenomenon is known as structure deformation-induced viscosity drop, which is common in pseudoplastic flow systems.

Shear-thinning behavior has been identified in ulvan dispersions derived from *U. fasciata* [10] and *Enteromorpha prolifera* [17], characterized by a reduction in apparent viscosity as the shear rate increases. This phenomenon occurs because of the alignment of polymer molecules in response to shear forces, which are influenced by the hydrodynamic properties of rigid and elongated molecular structures. At higher shear rates, the initially random orientation of the ulvan polymer chains gradually shifted and aligned with the flow direction. This reorientation minimizes the interactions between adjacent polymer chains, leading to a measurable decrease in viscosity.

4. Conclusion

Ulvan from *Ulva lactuca* exhibited variations in water-holding capacity and viscosity depending on the ultrasonic-assisted extraction period. This factor not only improved the extraction efficiency but also enhanced the properties. Among the different treatments, 2h ultrasonic extraction yielded the highest efficiency, with an extraction yield of 26.32%, WHC of 9.12 g water/g ulvan, OHC of 0.89 g oil/g ulvan, and viscosity of 8.8 cP. Furthermore, ultrasonication produced ulvan extracts with more defined fingerprint regions than the control.

Ulvan solutions demonstrated pseudoplastic behavior, particularly shear-thinning characteristics ($n < 1$), where viscosity was influenced by concentration and temperature. These properties suggest that ulvan has potential as a novel stabilizer in food applications, contributing to texture retention, product consistency, and prevention of ingredient separation.

Acknowledgements

We would like to acknowledge the financial support from the Indonesia Endowment Fund for Education (LPDP), Ministry of Finance (grant number: LOG-9324/LPDP.3/2024).

Conflict of interest

The authors declare no competing financial interests or personal relationships that could influence the results of this study.

References

[1] J. Chen *et al.*, “Effect of hydrocolloids on gel properties and protein secondary structure of silver carp surimi,” *J. Sci. Food Agric.*, vol. 100, no. 5, pp. 2252–2260, 2020, doi: 10.1002/jsfa.10254.

[2] B. Vardhanabhuti and S. Ikeda, “Isolation and characterization of hydrocolloids from monoi (Cissampelos pareira) leaves,” *Food Hydrocoll.*, vol. 20, no. 6, pp. 885–891, Aug. 2006, doi: 10.1016/J.FOODHYD.2005.09.002.

[3] M. Guidara *et al.*, “Effect of extraction procedures on the chemical structure, antitumor and anticoagulant properties of ulvan from Ulva lactuca of Tunisia coast,” *Carbohydr. Polym.*,

vol. 253, p. 117283, Feb. 2021, doi: 10.1016/j.carbpol.2020.117283.

[4] A. Carreira-Casais *et al.*, "Benefits and Drawbacks of Ultrasound-Assisted Extraction for the Recovery of Bioactive Compounds from Marine Algae," *Int. J. Environ. Res. Public Heal. 2021, Vol. 18, Page 9153*, vol. 18, no. 17, p. 9153, Aug. 2021, doi: 10.3390/IJERPH18179153.

[5] M. Kazemi, M. Fathi, K. Jahanbin, M. Taghdir, and S. Abbaszadeh, "Optimization of ultrasonic-assisted hot acidic solvent extraction of ulvan from Ulva intestinalis of the Persian Gulf: Evaluation of structural, techno-functional, and bioactivity properties," *Food Hydrocoll.*, vol. 142, p. 108837, Sep. 2023, doi: 10.1016/j.foodhyd.2023.108837.

[6] W. Ramadhan, S. Dyah Hardiningtyas, R. Fariz Pari, and D. Sevica, "Ekstraksi Polisakarida Ulvan dari Rumput Laut Ulva lactuca Berbantu Gelombang Ultrasonik pada Suhu Rendah," *J. Pengolah. Has. Perikan. Indones.*, vol. 25, no. 1, pp. 132–142, Apr. 2022, doi: 10.17844/JPHPI.V25I1.40407.

[7] S. Inoubli, M. D. Torres, and H. Domínguez, "Influence of Microwave hydrodiffusion and gravity (MHG) drying process on Ulva sp: Ulvan, molecular weight, rheology, and film development," *Lwt*, vol. 214, no. November, p. 117025, 2024, doi: 10.1016/j.lwt.2024.117025.

[8] Y. Yuan, X. Xu, C. Jing, P. Zou, C. Zhang, and Y. Li, "Microwave assisted hydrothermal extraction of polysaccharides from Ulva prolifera: Functional properties and bioactivities," *Carbohydr. Polym.*, vol. 181, pp. 902–910, Feb. 2018, doi: 10.1016/J.CARBPOL.2017.11.061.

[9] Y. Yang, L. Wei, and J. Pei, "Application of Bayesian modelling to assess food quality & safety status and identify risky food in China market," *Food Control*, vol. 100, no. January, pp. 111–116, 2019, doi: 10.1016/j.foodcont.2019.01.010.

[10] P. Shao, M. Qin, L. Han, and P. Sun, "Rheology and characteristics of sulfated polysaccharides from chlorophytan seaweeds Ulva fasciata," *Carbohydr. Polym.*, vol. 113, pp. 365–372, Nov. 2014, doi: 10.1016/j.carbpol.2014.07.008.

[11] H. Yaich *et al.*, "Effect of extraction procedures on structural, thermal and antioxidant properties of ulvan from Ulva lactuca collected in Monastir coast," *Int. J. Biol. Macromol.*, vol. 17, 2017, [Online]. Available: https://orbi.uliege.be/handle/2268/201468

[12] S. Feng *et al.*, "Optimization of Extraction Process, Structure Characterization, and Antioxidant Activity of Polysaccharides from Different Parts of Camellia oleifera Abel," *Foods*, vol. 11, p. 3185, 2022, doi: https://doi.org/10.3390/foods11203185.

[13] X. Shu, X. Liu, C. Fu, and Q. Liang, "Extraction, characterization and antitumor effect of the polysaccharides from star anise (Illicium verum Hook. f.)," *J. Med. Plants Res.*, vol. 4, no. 24, pp. 2666–2673, 2010, doi: 10.5897/jmpr09.438.

[14] J. Chen *et al.*, "Physicochemical properties and anti-oxidation activities of ulvan from Ulva pertusa Kjellm," *Algal Res.*, vol. 55, p. 102269, May 2021, doi: https://doi.org/10.1016/j.algal.2021.102269.

[15] R. Moreira, F. Chenlo, C. Silva, and M. D. Torres, "Rheological behaviour of aqueous methylcellulose systems: Effect of concentration, temperature and presence of tragacanth," *Lwt*, vol. 84, pp. 764–770, 2017, doi: 10.1016/j.lwt.2017.06.050.

[16] D. López-Barraza, A. Ortega-Ramos, E. Torregroza-Fuentes, S. E. Quintana, and L. A. García-Zapateiro, "Rheological and functional properties of hydrocolloids from pereskia bleo leaves," *Fluids*, vol. 6, no. 10, 2021, doi: 10.3390/fluids6100349.

[17] L. Qiao *et al.*, "Rheological properties, gelling behavior and texture characteristics of polysaccharide from Enteromorpha prolifera," *Carbohydr. Polym.*, vol. 136, pp. 1307–1314, 2016, doi: 10.1016/j.carbpol.2015.10.030.

[18] J. Wu *et al.*, "Ultrasonic disruption effects on the extraction efficiency, characterization, and bioactivities of polysaccharides from Panax notoginseng flower," *Carbohydr. Polym.*, vol. 291, no. December 2021, p. 119535, 2022, doi: 10.1016/j.carbpol.2022.119535.

[19] L. Wang *et al.*, "Effect of Ultrasonic Treatment on the Physicochemical Properties of Bovine Plasma Protein-Carboxymethyl Cellulose Composite Gel," *Foods*, vol. 13, no. 5, 2024, doi: 10.3390/foods13050732.

[20] X. Wang, M. Majzoobi, and A. Farahnaky, "Ultrasound-assisted modification of functional properties and biological activity of biopolymers: A review," *Ultrason. Sonochem.*, vol. 65, no. December 2019, 2020, doi: 10.1016/j.ultsonch.2020.105057.

[21] S. P. Gannasin, Y. Ramakrishnan, N. M. Adzahan, and K. Muhammad, "Functional and Preliminary Characterisation of Hydrocolloid from Tamarillo (Solanum betaceum Cav.) Puree," *Molecules*, vol. 17, pp. 6869–6885, 2012, doi: 10.3390/molecules17066869.

[22] H.-W. Yang, H.- Da Dai, W. Huang, and T. Sombatngamwilai, "Formulations of dysphagia-friendly food matrices with calorie-dense starchy thickeners and their stability assessments Huai-Wen," *J. Food Meas. Charact.*, vol. 14, no. 2, pp. 1–14, 2020, doi: https://link.springer.com/article/10.1007/s11694-020-00549-3.

[23] X. Yu *et al.*, "Effect of ultrasonic treatment on the degradation and inhibition cancer cell lines of polysaccharides from Porphyra yezoensis," *Carbohydr. Polym.*, vol. 117, pp. 650–656, 2015, doi: 10.1016/j.carbpol.2014.09.086.

[24] H. D. Goff and G. Q, "Handbook of Food Structure Development," in *Handbook of Food*

Structure Development, F. Spyropoulos, A. Lazidis, and I. Norton, Eds., Cambridge, UK: The Royal Society of Chemistry, 2019, pp. 1–28. doi: 10.1039/9781788016155.

[25] S. Y. Seo, Y. R. Kang, Y. K. Lee, J. H. Lee, and Y. H. Chang, "Physicochemical, molecular, emulsifying and rheological characterizations of sage (Salvia splendens) seed gum," *Int. J. Biol. Macromol.*, vol. 115, pp. 1174–1182, 2018, doi: https://doi.org/10.1016/j.ijbiomac.2018.04.173 0141-8130/©.

[26] J. Wu, Y. Rong, Z. Wang, Y. Zhou, S. Wang, and B. Zhao, "Isolation and characterisation of sericin antifreeze peptides and molecular dynamics modelling of their ice-binding interaction," *Food Chem.*, vol. 174, pp. 621–629, 2015, doi: https://doi.org/10.1016/j.foodchem.2014.11.100.

[27] M. Marcotte, A. R. T. Hoshahili, and H. S. Ramaswamy, "Rheological properties of selected hydrocolloids as a function of concentration and temperature," *Food Res. Int.*, vol. 34, no. 8, pp. 695–703, Jan. 2001, doi: 10.1016/S0963-9969(01)00091-6.