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Optimizing the Dehydration and Quality Preservation of Sea Grapes (*Caulerpa lentillifera*)

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Abstract.
The preservation of Vietnamese sea grapes (*Caulerpa lentillifera*) still faces major limitations due to their short shelf life and rapid deterioration of their sensory, aesthetic, and nutritional qualities. This results from commonly used NaCl brine rather than better alternative processing approaches.
This study aimed to optimize the parameters for preserving Vietnamese sea grapes. In particular, we optimized dehydration and color fixation techniques to enhance their sensory quality and shelf life.
Optimal conditions were identified as blanching at 90°C for 10 s, rapid cooling at 10–15°C, and soaking in a color-fixation solution (15% NaCl + 5% sorbitol) for 10–15 min. The treated sea grapes demonstrated a superior color quality compared to common commercial products, with the green color index of 117.93 ± 44.86 and color intensity of 94.32 ± 45.36. Other improvements included a possible shelf life extension by 4–6 weeks, a decrease of 20–25% in spoilage rates, and a reduction of 10–15% in preservation and transportation costs. This can increase the net profit by 15–20%, as well as improve the product's efficiency and competitiveness.
The developed method extends the shelf life of Vietnamese sea grapes, reduces their spoilage, and lowers preservation costs. This enables the product to meet international quality standards, enhancing its value and competitiveness. The remaining challenges include high initial investment, temperature control, staff training, and quality control systems. Future studies should identify changes in essential nutrients under long-term real-life transportation and storage conditions.

Keywords. Seaweed, *Caulerpa lentillifera*, color fixation, thermal blanching, dehydration

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Оптимизация технологии сушки и хранения морского винограда (*Caulerpa lentillifera*)

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Аннотация.
Вьетнамский морской виноград (*Caulerpa lentillifera*), также известный как каулерпа чечевицеобразная, относится к скоропортящимся продуктам: в процессе транспортировки и хранения быстро теряет свои органолептические свойства и пищевую ценность. Для сохранения вкусовых качеств и товарного вида морского винограда традиционно используется раствор поваренной соли, однако существуют и альтернативные, более эффективные методы. Цель данного исследования – оптимизировать параметры консервирования вьетнамского морского винограда, в частности методы сушки и сохранения цвета, для улучшения органолептических свойств и продления срока хранения.
Оптимальной технологией обработки морского винограда оказалось бланширование в течение 10 с при температуре 90 °C с последующим быстрым охлаждением до 10–15 °C и замачиванием в растворе (15 % NaCl + 5 % сорбита) на 10–15 мин для фиксации цвета. Обработанный таким способом морской виноград сохранял цвет лучше, чем его коммерческие образцы: индекс зеленого цвета опытного образца составил 117,93 ± 44,86, а интенсивность – 94,32 ± 45,36. Удалось продлить срок годности опытного образца на 4–6 недель и снизить показатели порчи на 20–25 %. Разработанная технология сушки позволит сократить расходы на хранение и транспортировку морского винограда на 10–15 % и увеличить чистую прибыль на 15–20 %, что существенно улучшит конкурентные качества продукта.
Представленный в данной статье метод дает возможность продлить срок годности вьетнамского морского винограда, сохранить органолептические свойства и понизить расходы на его хранение и транспортировку. Технология позволяет получить продукт, соответствующий международным стандартам качества, что существенно повысит его ценность и конкурентоспособность на рынке. Нерешенными остались проблемы высоких первоначальных инвестиций, контроля температуры, обучения персонала и поддержания системы контроля качества. В будущем предстоит провести тщательный анализ изменений, которые претерпевает питательный состав морского винограда в условиях длительной транспортировки и хранения.

Ключевые слова. Морские водоросли, *Caulerpa lentillifera*, фиксация цвета, термическое бланширование, сушка

Финансирование. Данное исследование проводилось при финансовой поддержке Министерства сельского хозяйства и окружающей среды Вьетнама в рамках проекта «Исследование и разработка новых технологий коммерческого выращивания и переработки экономически ценных видов морских водорослей Вьетнама» (№ 101/2022/HD-KHCN-TS).

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Introduction

Sea grapes *(Caulerpa lentillifera*) are a tropical seaweed species with high nutritional and economic value. They are rich in compounds such as vitamin A, B-complex vitamins, vitamin C, polyphenols, essential fatty acids (EPA, DHA), and trace minerals such as iodine, iron, and calcium [1–3]. However, these critical compounds (particularly chlorophyll, vitamin A, and iodine) are highly susceptible to degradation or significant loss during processing and storage, which directly affects the product's color, texture, and nutritional value [3, 4].

In Viet Nam, sea grapes are mainly cultivated in the south-central coastal provinces such as Khanh Hoa and Phu Yen, with an annual production of around

180,000 tons (Fisheries Sector Summary Report, Ministry of Agriculture and Rural Development, 2023). Despite this potential, the quality of Vietnamese sea grapes still faces major limitations. After only 3–4 weeks of storage using traditional methods (saturated NaCl brine), the product significantly loses its crispness, fades from vibrant green to yellow, and becomes less competitive in premium markets such as Japan, South Korea, and Europe. Economic losses are estimated at millions of USD annually due to reduced commercial value and brand reputation [5].

Improving preservation techniques for sea grapes has become an urgent necessity, not only to reduce post-harvest losses but also to enhance the global competitiveness of Vietnamese seaweed products. The main reason behind the rapid deterioration lies in the conventional use of high-concentration NaCl brine. This preservation technique causes cellular shrinkage, disrupts the bound water structure inside the cells, and accelerates chlorophyll degradation into pheophytin under the influence of Na^+ and Cl^- ions. This not only reduces the vitamins and iodine contents but also leads to drastic changes in the sensory qualities and nutritional value [6, 7].

Previous studies have shown that enzymes such as polyphenol oxidase, which catalyzes the oxidation of phenolic compounds into brown pigments, and peroxidase, which promotes hydrogen peroxide degradation and damages cell structure, accelerate oxidation and discoloration, ultimately degrading the product's quality [8, 9]. International research by Wanida *et al.* [3] and Satmalee *et al*. [9] demonstrated the effectiveness of thermal blanching in deactivating these enzymes and thereby better preserving the cell structure and color. Sorbitol, a polyol with strong water-binding properties, has also been shown to significantly improve water retention and stabilize food cell structures during preservation processes [10]. However, most previous studies applied these techniques independently, lacking a comprehensive, optimized combination of thermal blanching and sorbitol treatment parameters for *C. lentillifera* such as blanching temperature, blanching time, and solution concentration.

Our study aimed to develop an optimized preservation process for sea grapes by combining thermal blanching and sorbitol-enhanced color fixation techniques. This approach was expected to prolong shelf life, improve sensory qualities, and minimize nutritional losses, thereby meeting the international food quality standards and boosting the export value of Vietnamese sea grapes.

We proposed a technical process based on the preliminary experiments and existing scientific evidence. In particular, blanching at 90°C for 10–15 s was selected due to its effectiveness in inactivating polyphenol oxidase and peroxidase while maintaining the optimal cell integrity. Similarly, a preservation solution of 15% NaCl and 5% sorbitol was identified as the optimal ratio to preserve the cellular structure, minimize the loss of bound water, and retain the key nutrients in sea grapes. Our hypothesis was that applying these conditions in tandem might improve the structural recovery of sea grapes to over 90% and maintain the stable color indicators (CIE Lab or RGB) for a minimum storage duration of six months.

Our results address the urgent challenge of preservation and contribute to enhancing the competitiveness of Viet Nam's sea grape industry in the global markets. Their practical significance is in helping Vietnamese enterprises meet the international standards such as Codex Alimentarius, Japan's JAS, and the EU's food safety regulations, thereby boosting the export value and fostering sustainable development in the seaweed sector.

Study objects and methods

Study objects. Fresh sea grapes (*Caulerpa lentillifera*) were supplied by the DT Food Company, Nha Trang, Khanh Hoa, Viet Nam. The raw materials were harvested and transported to the laboratory within 24 h using specialized refrigerated vehicles, maintaining a constant temperature of 4°C and avoiding direct light exposure to ensure quality. Material selection criteria included: upright stem length > 6 cm, natural green color, no bruising, intact beads, characteristic marine odor, and moisture content of 95 ± 1%. The chlorophyll content was determined by spectrophotometry based on the Lichtenthaler method (1987), using 80% acetone solvent and measuring at wavelengths of 663 and 645 nm, yielding 1.2 ± 0.05 mg/g [4]. The iodine content was analyzed using the AOAC 992.24 standard method, with a result of 25 ± 1 mg/kg [5].

Supplementary materials. Table salt (NaCl) met the National Technical Regulation (Circular No. 08/2021/TT-BNNPTNT); sorbitol conformed to Vietnamese Standard TCVN 6465:2008.

Research methods. ***Blanching and rapid cooling procedure***. Sea grapes were blanched in a 5% diluted NaCl solution at a seaweed-to-solution ratio of 1:10 (w/v) at various temperatures (80, 85, 90, and 95°C) for durations of 5, 10, 15, and 20 s to inactivate polyphenol oxidase and peroxidase enzymes, based on the prior seaweed heat treatment studies [4, 6]. Immediately after blanching, the samples were rapidly cooled by immersing in an ice-water bath at a water-to-seaweed volume ratio of 5:1. The temperature was maintained between 10–25°C by continuously adding ice over a 3-min period to effectively terminate the enzyme reaction, as determined from the preliminary trials.

Color fixation treatment. The color fixation solution consisted of NaCl (10, 15, and 20%) combined with 5% sorbitol. The sea grapes were soaked in the solution at a 1:1 solution-to-seaweed ratio for 5, 10, 15, and 20 min, based on the preliminary experiments and studies on solution diffusion into seaweed cells [5, 6].

Color analysis. Images of the sea grape samples were taken using a Cannon IXY Digital 510IS camera

(12.1 megapixels, Tokyo, Japan). The samples were placed on a black background at a fixed distance of 30 cm from the camera, ISO 100, with fixed focal length. Prior to analysis, color standardization was performed using an X-Rite ColorChecker and the white balance tool in Image J software (National Institutes of Health, Bethesda, Maryland, USA). The analysis parameters included color intensity, as well as red, green, and blue values.

Structural recovery assessment. A 10 g portion of fully dehydrated sea grape samples (m_1 = 10 g) was soaked in 100 ml of distilled water at room temperature (25 ± 1°C) for 10 min without stirring. The samples were then removed, blotted dry with Whatman No.1 filter paper for 5 min, and weighed again to determine the post-rehydration mass (m_2). Structural recovery (H, %) was calculated using the formula:

$$H = \frac{m_2 - m_1}{m_1}$$

where m_1 is the initial weight of the dehydrated sea grape sample (fixed at 10 g) and m_2 is the weight after rehydration and blotting.

Sensory evaluation. Before sensory evaluation, the sea grape samples were rehydrated by soaking in distilled water at room temperature (25 ± 1°C) for 10 min and then blotted dry with Whatman No.1 filter paper for 5 min. Each sample was weighed precisely at 5 g and placed on a clean white porcelain dish coded randomly with three-digit numbers to prevent bias. A panel of 10 experts with at least 5 years of experience and training according to ISO 8586:2012 standards evaluated the samples in a temperature-controlled room (25 ± 1°C) with standardized lighting. The average scores from their independent assessments were calculated based on the following criteria and weighting coefficients: Color (1.2), Odor (0.8), Taste (1.0), and Texture (1.0), as detailed in Table.

Data processing. All the experiments were conducted in triplicate. The results were presented as mean ± standard deviation (M ± SD). The data were analyzed using one-way ANOVA and Tukey's HSD test at a significance level of $p < 0.05$. Statistical analyses were performed using IBM SPSS software version 26 and Image J (Fig. 1).

Results and discussion

Optimizing the dehydration process for sea grapes. ***Blanching temperature***. We studied the effects of blanching temperature (80, 85, 90, and 95°C) on the structural recovery and color stability of sea grapes (*Caulerpa lentillifera*) (Figs 2 and 3).

Table. Sensory evaluation scoring for dehydrated sea grapes (*Caulerpa lentillifera*)

Таблица. Органолептическая оценка высушенного морского винограда (*Caulerpa lentillifera*)

Criterion	Raw Score	Description	Coefficient
Color	5	Deep green; after soaking, very similar to fresh seaweed	1.2
	4	Deep green; fairly similar to fresh seaweed	
	3	Slightly pale green; somewhat lighter than fresh seaweed	
	2	Pale green; very light after soaking	
	1	Very pale green with white spots; unevenly green after soaking	
	0	Extremely pale, nearly whitish; losing green color after soaking	
Odor	5	Very mild seaweed aroma, no off-smell; retaining characteristic scent after soaking	0.8
	4	Mild seaweed smell; fairly characteristic after soaking	
	3	Noticeable seaweed smell; retaining core scent	
	2	Lacking distinct aroma, with some slight unfamiliar smell	
	1	Losing seaweed scent, with strong off-odor	
	0	No characteristic aroma, with unpleasant foreign odor	
Taste	5	Strong characteristic flavor of fresh sea grapes; well-retained after soaking	1.0
	4	Characteristic sea grape flavor	
	3	Mildly noticeable characteristic flavor	
	2	Very weak sea grape taste	
	1	No recognizable sea grape flavor	
	0	Overly salty or unpleasant off-flavor, spoiled product	
Texture	5	Intact, crisp strands; evenly rehydrated; swelling back to near-original state after soaking	1.0
	4	Intact and crispy; relatively evenly rehydrated; swelling back quite well	
	3	Partially broken, less crispy, unevenly rehydrated; with some beads detached after soaking	
	2	Broken and soft strands, not disintegrated; minimal swelling, minor bead loss	
	1	Severely broken, partially fragmented strands; poorly rehydrated	
	0	Fully broken, powdery, with no swelling capability	

Note: Evaluation framework based on TCVN 14142:2024 and TCVN 3215:79, adjusted for product relevance.

Примечание: Оценка проводилась на основе скорректированных Национальных Стандартов TCVN 14142:2024 и TCVN 3215:79.

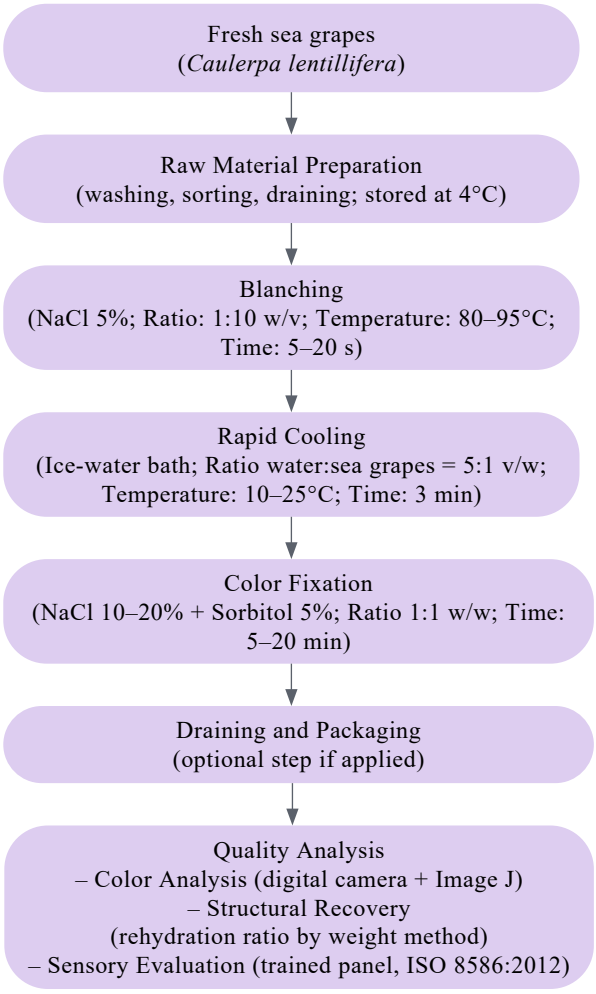


Figure 1. Flowchart of research procedure

Рисунок 1. Схема исследования

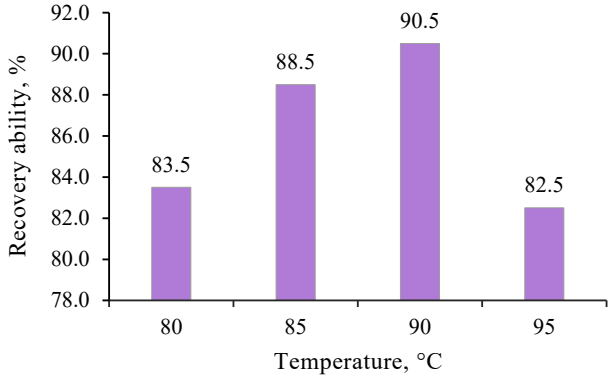


Figure 2. Effect of blanching temperature (80–95°C) on the structural recovery of *Caulerpa lentillifera*. The values represent M ± SD (n = 3). (Visuals: 80 → 85 → 90 → 95°C)

Рисунок 2. Зависимость структурного восстановления морского винограда (*Caulerpa lentillifera*) от температуры бланширования (80–95 °C): средние значения ± стандартное отклонение (n = 3); температура бланширования – 80 → 85 → 90 → 95 °C

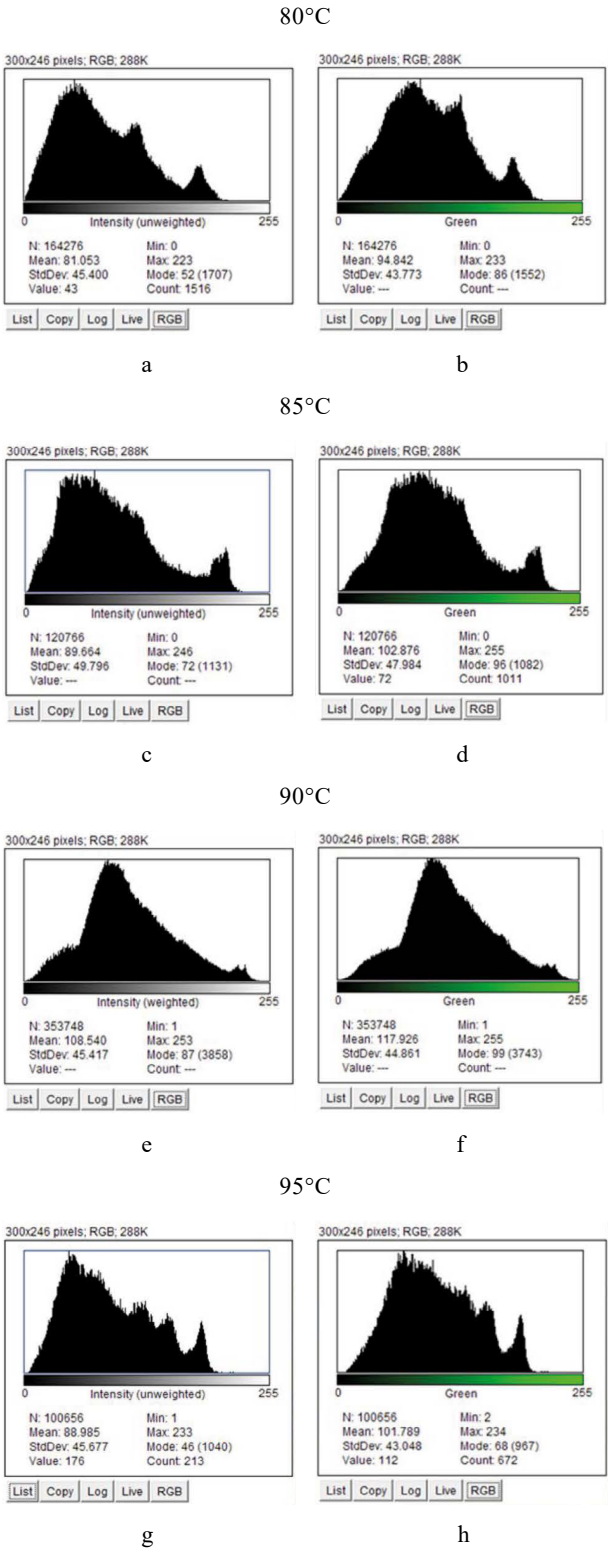


Figure 3. Histogram (Image J) illustrating the effect of blanching temperature (80, 85, 90, and 95°C) on color intensity and green index of dehydrated *Caulerpa lentillifera*

Рисунок 3. Гистограмма (J) зависимости интенсивности и индекса зеленого цвета в образцах высушенного морского винограда (*Caulerpa lentillifera*) от температуры бланширования (80, 85, 90, 95 °C)

According to Fig. 2, the structural recovery of sea grapes increased significantly as the blanching temperature rose from 80°C (81.67%) to 90°C (90.87%), before dropping to 82.37% at 95°C. One-way ANOVA and Tukey's HSD test ($p < 0.05$) confirmed that the structural recovery at 90°C was significantly different compared to the other temperature levels. This is because 90°C offers an effective balance between water removal and enzyme inactivation without causing excessive damage to the cellular structure of sea grapes.

The color intensity and the green index were quantified using digital image analysis with Image J software (Fig. 3). At a blanching temperature of 90°C, the color intensity and the green index reached their peak values of 108.54 (Fig. 3e) and 117.93 (Fig. 3f), respectively. In contrast, 80°C yielded lower values of 81.05 and 94.84, respectively (Fig. 3a and b), while 85°C resulted in 89.55 and 102.88, respectively (Fig. 3c and d). The excessively high blanching temperature of 95°C caused structural damage and accelerated the conversion of chlorophyll into pheophytin. This significantly reduced the color indicators to 88.99 (Intensity) and 101.79 (Green) (Fig. 3g and h). According to previous research [7], temperatures above 90°C rapidly displaced Mg^{2+} ions from the chlorophyll molecule, converting it into pheophytin and leading to chlorophyll pigment instability.

Furthermore, our results indicated a strong correlation between structural recovery and color stability. The optimal blanching temperature of 90°C effectively preserved cellular structure, thereby minimizing chlorophyll loss and maintaining the characteristic green color of the sea grapes.

Although we did not directly measure the activity of polyphenol oxidase and peroxidase, prior studies [8, 9] support that 90°C is sufficient for effective inactivation of these oxidative enzymes. While the referenced studies were conducted on carrots [8] and *Ulva rigida* [9], the effect of heat treatment on the cell structure and pigment degradation was comparable, providing a sound explanation for our results with *C. lentillifera*.

The optimal blanching temperature of 90°C not only enhanced the product quality control but also improved the structural recovery and color stability of sea grapes. This significantly extended the product's shelf life and fulfilled the stringent quality requirements of the demanding markets such as Japan, South Korea, and Europe.

Blanching time. After preliminary processing and cleaning, the fresh sea grape samples were blanched for 5, 10, 15, and 20 s to evaluate the time's effect on their structural recovery and color stability (Figs 4 and 5).

Our results indicated that the highest structural recovery (90.77%) was achieved at a blanching time of 10 s (Fig. 4). Compared to this optimal duration, the structural recovery at a shorter blanching time (5 s) decreased by 12.88%, while longer durations (15 and 20 s) showed respective decreases of 4.46 and 6.85%. These differences were statistically significant, as confirmed by one-way ANOVA with Tukey's HSD test ($p < 0.05$).

The color intensity and the green index were analyzed using standardized digital imaging processed with Image J software (National Institutes of Health, USA) under consistent photographic and color calibration conditions described in the Methods section (Fig. 5). The blanching time of 10 s yielded the highest values of 104.78 for color intensity and 117.02 for the green index. These values decreased markedly at other blanching times reaching 83.21 and 95.71 at 5 s, 86.25 and 103.41 at 15 s, and only 77.00 and 92.92 at 20 s, respectively.

This phenomenon is attributed to the role of blanching in deactivating polyphenol oxidase (PPO), the enzyme primarily responsible for oxidizing phenolic compounds and forming pigments that destabilize chlorophyll. A blanching time of 10 s appears sufficient for optimal PPO inactivation, thereby protecting chlorophyll and maintaining color stability. Although we did not directly measure PPO activity, our results align with those in [8], where blanching times under 10 s were inadequate for complete enzyme inactivation, reducing the effectiveness of pigment and structural preservation. In contrast, longer blanching times (15–20 s) resulted in protein denaturation and excessive pectin solubilization in the cell membranes. This caused serious structural damage, reduced bound water retention, and accelerated chlorophyll conversion to pheophytin. These findings support prior observations regarding thermal over processing and plant cell damage [7].

Our results clearly reveal a correlation between structural recovery and color stability, suggesting that stable cellular structure is crucial for preserving chlorophyll in sea grapes. The optimal blanching time of 10 s found in

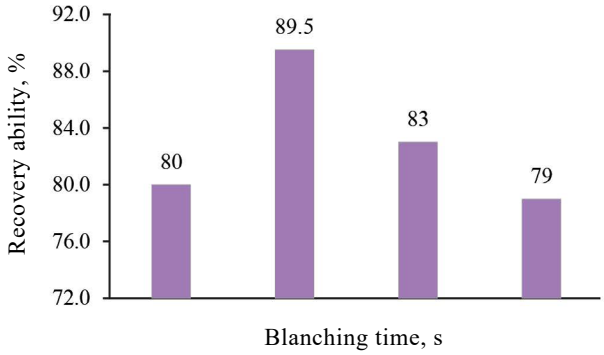


Figure 4. Effect of blanching time (5–20 s at 90°C) on the structural recovery of *Caulerpa lentillifera*. The values are expressed as M ± SD based on three experimental replicates (n = 3).
(Visuals: Blanching time 5 → 10 → 15 → 20 s)

Рисунок 4. Зависимость структурного восстановления морского винограда (*Caulerpa lentillifera*) от продолжительности бланширования (5–20 с; 90 °C): среднее значение ± стандартное отклонение (n = 3); время бланширования – 5 → 10 → 15 → 20 с

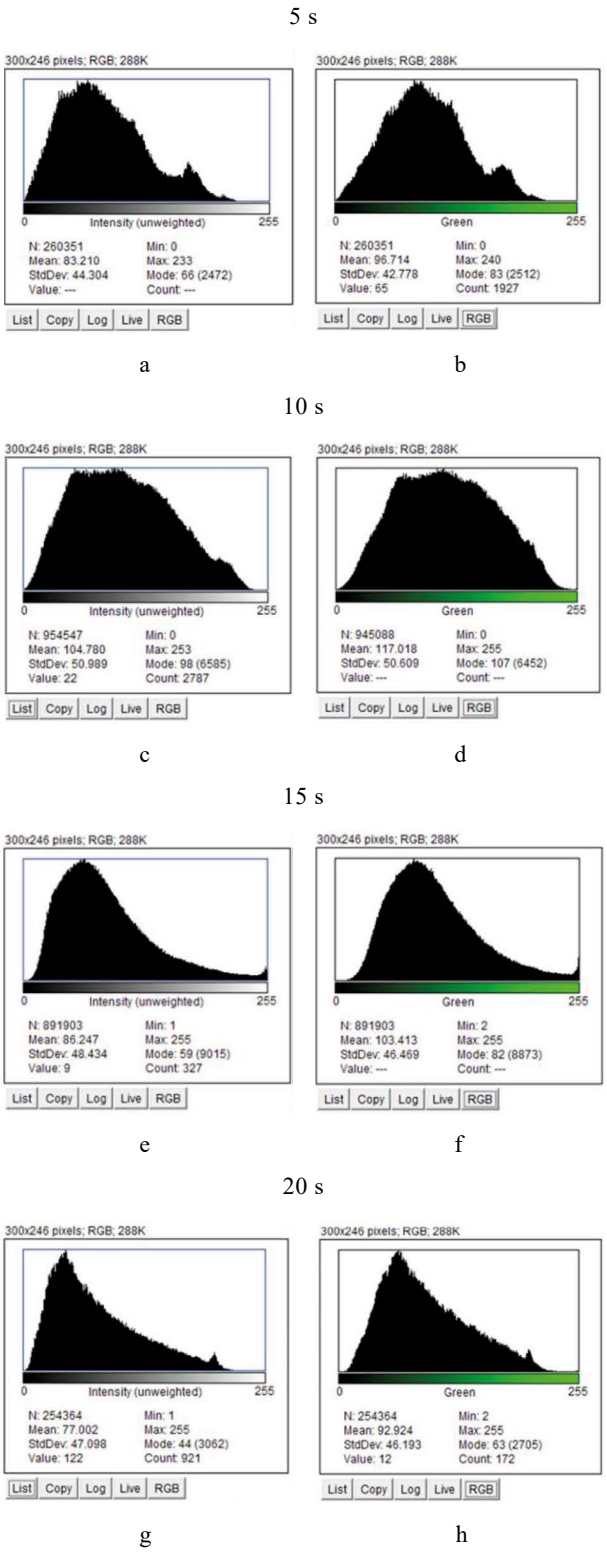


Figure 5. Histogram (Image J) showing the effect of blanching time (5, 10, 15, and 20 s) on color intensity and green index of dehydrated sea grapes. The values are the average of three independent replicates (n = 3)

Рисунок 5. Гистограмма (J) зависимости интенсивности и индекса зеленого цвета высушенного морского винограда (*Caulerpa lentillifera*) от продолжительности бланширования (5, 10, 15, 20 с): среднее значение (n = 3)

our study is consistent with previous research on freeze-dried *C. lentillifera* [4]. In the referenced study, 10 s was sufficient for inactivating polyphenol oxidase without notable cellular damage.

The optimal blanching time of 10 s enabled maximal preservation of both structure and color, extending the shelf life of sea grapes by at least several weeks, compared to the products treated for suboptimal blanching durations. This aligns with earlier research [2] confirming that optimal blanching conditions significantly enhance the commercial storage period of sea grapes. Furthermore, proper blanching time helps reduce product spoilage during storage and export transportation. This improves the product's commercial value and economic efficiency, while fulfilling strict international quality standards required by the export markets such as Japan, South Korea, and Europe.

Post-blanching treatment of sea grapes. The immediate cooling of blanched sea grapes induces a rapid temperature shift, which prevents the rupture of the cell structure caused by prolonged high temperatures. Additionally, this step allows the cells to contract, thereby reducing the loss of water-soluble nutrients. The results of the post-blanching rinsing are presented in Fig. 6.

One-way ANOVA combined with Tukey's test ($p < 0.05$) showed that the rinsing temperature significantly influenced the sensory quality (especially crispness and chewiness) of the final sea grape product. The sensory scores were evaluated on a 20-point scale by a panel of 10 trained experts in accordance with ISO 8586:2012 standards. Notably, the lower the rinsing temperature, the better the sensory quality observed. At rinsing temperatures of 10 and 15°C, the sea grapes achieved the highest sensory scores of 17.58 and 17.39 points, respectively.

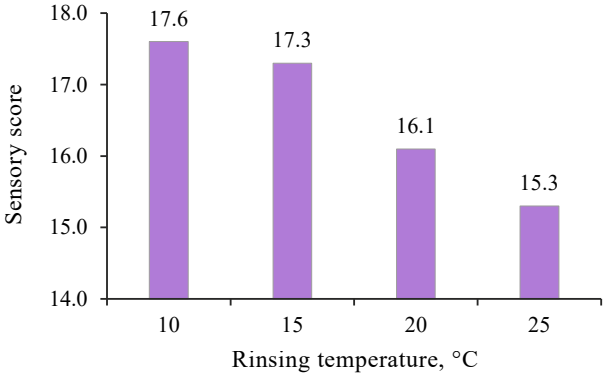


Figure 6. Effect of post-blanching rinsing temperature (10–25°C) on the sensory quality (crispness, chewiness) of *Caulerpa lentillifera*. The values are presented as M ± SD from three experimental replicates (n = 3)

Рисунок 6. Зависимость органолептических показателей морского винограда (*Caulerpa lentillifera*) от температуры ополаскивания после бланширования (10–25 °C) (хрусткость, разжевываемость): среднее значение ± стандартное отклонение (n = 3)

In contrast, at a rinsing temperature close to ambient conditions (25°C), the score significantly declined to 15.20 points.

This might be because blanching at high temperatures (e.g., 90°C) followed by sudden cooling to low temperatures (10–15°C) greatly reduces the kinetic energy of molecules. This slowdown or inhibition of chemical reactions prevents the release of Mg^{2+} ions from the chlorophyll molecule and avoids excessive denaturation of proteins and pectin [7]. Consequently, chlorophyll is more effectively preserved rather than converted to pheophytin. The rinsing temperature of 10°C maintained maximum color intensity and green index at 98.33 and 110.74, respectively. In contrast, these values dropped significantly at 25°C, with the intensity at 86.88 and the green index at 104.02.

Furthermore, low temperatures help retain intracellular bound water, minimizing the loss of water-soluble nutrients such as vitamins and minerals. This preserves the crisp and chewy texture of the product, keeping it close to that of fresh material. On the other hand, rinsing at near-room temperature (25°C) slows the cooling process, prolonging oxidative reactions and protein / pectin denaturation in the cell membrane. This results in significant cellular damage, a lower water retention capacity, and a substantial loss of texture quality [8].

However, to further confirm the protective effects of this technique on nutrients and pigmentation, the study should include additional analysis of vitamin contents and other key nutrients. Furthermore, storage duration and economic efficiency should be assessed through practical shelf-life simulations and cost-benefit analyses.

These findings are consistent with previous studies on *C. lentillifera*, confirming that rapid post-blanching temperature changes are optimal for preserving the cell structure and sensory qualities in seaweed products [2, 4]. Applying an optimized rinsing temperature of 10–15°C can extend the shelf life by several weeks, compared to room-temperature rinsing. In addition, this temperature range can reduce spoilage during storage and transportation, thereby enhancing the commercial value and competitiveness of the product in the demanding international markets of Japan, South Korea, and Europe.

Optimizing the color fixation solution. ***The concentration of the color fixation solution***. The effects of the immersion solution concentration (NaCl combined with sorbitol) on the color fixation capacity of sea grapes are presented in Fig. 7.

One-way ANOVA and Tukey's test ($p < 0.05$) confirmed the statistically significant differences in both the color intensity and the green index between the treatment using 15% NaCl + 5% sorbitol and the other two treatments (10 and 20% NaCl). Specifically, the highest color intensity (98.33; SD = 51.363) and green index (110.74; SD = 51.474) were achieved with the 15% NaCl + 5% sorbitol solution. However, the relatively high standard deviations indicate potential errors during image capture and analysis, suggesting a need to improve image standardization or increase the number of replicates for more consistent results.

At a lower NaCl concentration (10%), the color intensity and the green index were significantly lower at 92.32 and 104.84, respectively. This may be attributed to insufficient osmotic pressure to effectively remove free water from the cells. This in turn leads to incomplete inhibition of the polyphenol oxidase enzyme and continued oxidation of chlorophyll, compromising the

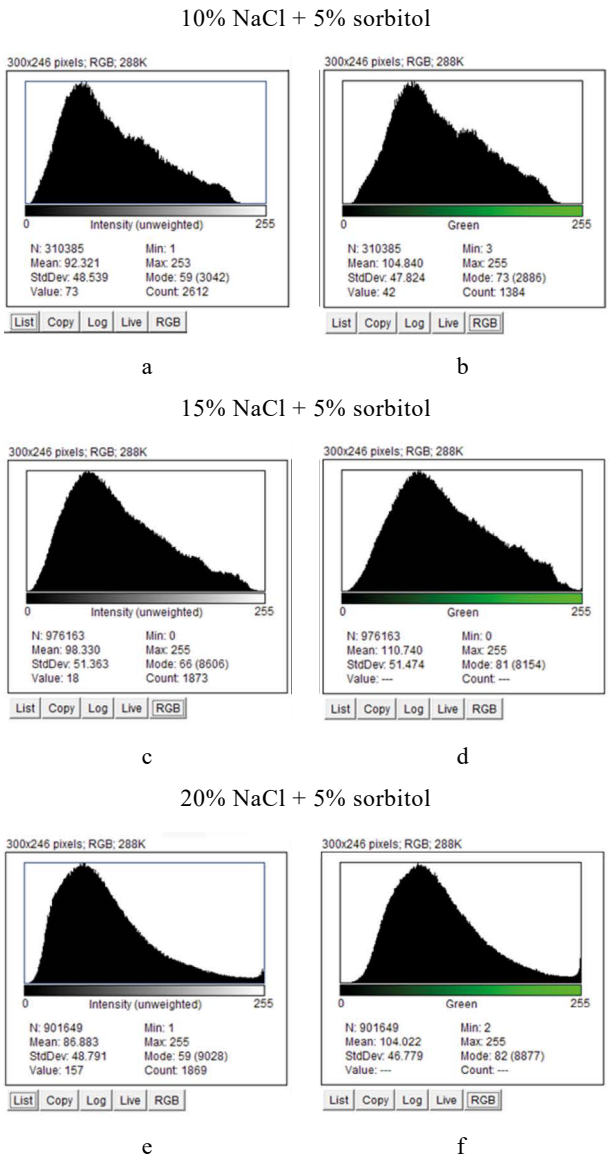


Figure 7. Effect of color fixation solution concentrations (10–20% NaCl + 5% sorbitol) on the color fixation capacity of *Caulerpa lentillifera* (Image J). The values are presented as M ± SD from three independent replicates (n = 3)

Рисунок 7. Зависимость качества цвета морского винограда (*Caulerpa lentillifera*) (J) от концентрации раствора (10–20% NaCl + 5% сорбита): среднее значение ± стандартное отклонение (n = 3)

color retention capacity of the sea grapes [1, 2]. Conversely, at a higher NaCl concentration (20%), excessively high osmotic pressure caused a severe loss of bound water, resulting in significant cellular damage and rapid removal of Mg^{2+} ions from the chlorophyll molecule. This accelerated the conversion of chlorophyll into pheophytin, reducing the color intensity and the green index to 86.88 and 104.02, respectively [3, 4].

The selection of 5% sorbitol concentration was based on the preliminary trials and prior studies, confirming that this level provides an optimal balance between water retention and cellular structure stabilization without causing structural damage due to excessive osmotic stress [2]. Sorbitol, a polyol containing multiple hydroxyl groups, forms strong hydrogen bonds with intracellular water in sea grapes, thereby stabilizing bound water and effectively preventing excessive shrinkage or cellular damage during dehydration. As a result, the sea grapes retain their crispness, chewiness, and vibrant color [5].

The optimized fixation solution (15% NaCl + 5% sorbitol) not only stabilizes color and structure but also extends the shelf life of the product by at least 4–6 weeks under refrigerated conditions. In addition, it significantly reduces spoilage rates during transportation and storage by approximately 20–30%. This in turn leads to cost savings, improved profitability, and better compliance with the strict international export standards such as Codex Alimentarius, Japan's JAS, and EU food safety regulations [2, 6].

The time of immersion in the color fixation solution. We investigated the effect of different times (5, 10, 15, and 20 min) of immersion in the color fixation solution (15% NaCl + 5% sorbitol) on the color retention ability of *C. lentillifera* (Fig. 8).

The highest color intensity values were recorded at 10 min (107.664 ± 52.834) and 15 min (115.965 ± 49.831) of immersion. Similarly, the green index reached its optimal levels at these durations, with 124.673 ± 53.649 and 126.173 ± 50.128, respectively. However, the standard deviation (Stdev) was relatively high (~ 50% of the mean), which might be due to uncontrolled lighting and camera angle during image capture. To address this issue, the research team recommended using a professional photography box to ensure consistent lighting, distance, and angle to reduce analytical error.

One-way ANOVA and Tukey's HSD test ($p < 0.05$) revealed that the immersion times of 10 and 15 min produced statistically significant differences compared to shorter (5 min) and longer (20 min) immersion times. Specifically, a short immersion time of 5 min resulted in a lower color intensity of 105.726 (8.8% lower than at 15 min), and a lower green index of 120.807 (4.3% lower). On the other hand, the 20-min immersion led to the sharpest decrease in color retention, with the color intensity dropping to 85.021 (26.7% lower than at 15 min) and the green index falling to 111.698 (11.5% lower).

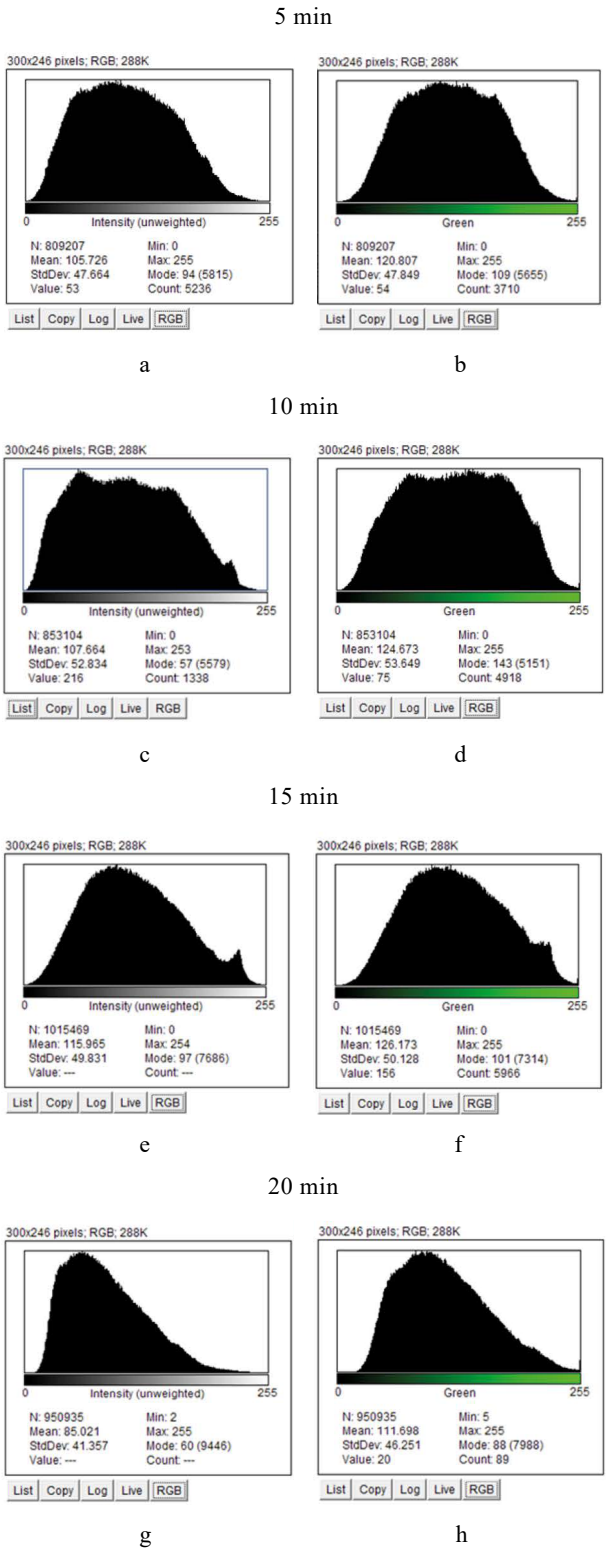


Figure 8. Effect of the time of immersion in the color fixation solution (5, 10, 15, and 20 min) on the color retention of *Caulerpa lentillifera* (Image J). The values represent M ± SD from three independent replicates (n = 3)

Рисунок 8. Зависимость качества цвета морского винограда (*Caulerpa lentillifera*) (J) от времени погружения в раствор (5, 10, 15, 20 мин): среднее значение ± стандартное отклонение (n = 3)

The short immersion time (5 min) was insufficient for the NaCl and sorbitol solution to fully penetrate the cellular structure, preventing the achievement of optimal osmotic equilibrium. As a result, a high level of free water remained within the cells, allowing polyphenol oxidase enzymes to remain active and promote oxidation of chlorophyll pigments. Conversely, prolonged immersion (20 min) resulted in excessive dehydration due to high osmotic pressure, significantly damaging cell membranes. This structural damage accelerated the hydrolysis of Mg^{2+} from chlorophyll, converting it into pheophytin and thus markedly reducing color retention efficiency [11]. Our preliminary experiments indicated that the optimal immersion time to achieve effective penetration and osmotic equilibrium without damaging cell structure was between 10–15 min. This finding is consistent with earlier studies by Nguyễn Thị Mỹ Trang and Vũ Ngọc Bội [2] and Hoàng Thái Hà [4], which demonstrated similar impacts of immersion duration on cellular integrity, chlorophyll stability, and overall product quality.

The choice of 5% sorbitol was based on preliminary research, confirming that this level provides an optimal balance between water retention, textural preservation, and minimization of cell shrinkage or deformation. This concentration proved superior compared to both higher (7–10%) and lower (3%) concentrations. These findings align with those of Nguyễn Thị Mỹ Trang and Vũ Ngọc Bội [2], who also identified an optimal immersion time of 10–15 min for preserving the quality of *C. lentillifera*.

Based on this study and previous findings, the optimal immersion time of 15 min is expected to extend the shelf life of sea grapes by 4–6 weeks and reduce spoilage rates by ~ 25–30%. This improvement could lead to 15–20% savings in total preservation and transportation costs, thereby enhancing the economic efficiency and international market competitiveness of the product.

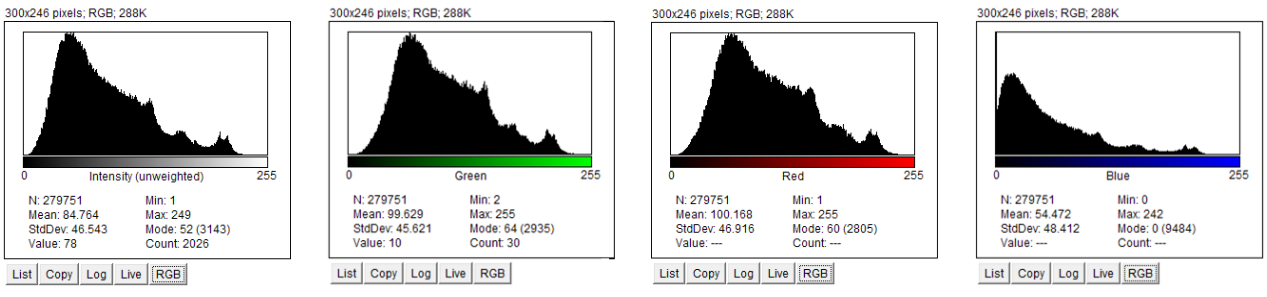
Comparative analysis of color quality between the experimental and the commercial dehydrated sea grape products. The color quality of the final sea grape product was analyzed and compared with that of two commercial dehydrated sea grape products commonly available on the market, Trí Tín and D&T. Three independent samples of each brand were randomly collected from the local markets at the time of the study to ensure objectivity and representativeness. They were analyzed by using Image J software (Figs 9 and 10).

The findings showed that the green index of the final product reached 117.926 ± 44.861, which was significantly higher than that of the commercial dehydrated samples (99.629 ± 45.621). Similarly, the color intensity of the experimental product was considerably higher than that of the commercial counterparts, recorded at 94.321 ± 45.362 and 84.764 ± 46.543, respectively. However, high standard deviations (~ 40–50% of the mean) suggested potential inconsistencies in the analysis conditions. Therefore, to enhance reliability and result consistency, we used professional imaging equipment and implemented strict control over the lighting conditions, camera angles, and sample standardization.

Statistical analysis using an independent sample *t*-test ($p < 0.05$) confirmed statistical significance of the green index and color intensity differences between the experimental and commercial products.

These results were due to the new technical solution that we employed to simultaneously optimize the key processing parameters, including blanching temperature (90°C), blanching duration (10–15 s), color fixation solution concentration (15% NaCl + 5% sorbitol), and optimal immersion time (15 min). These conditions preserved the cellular structure and effectively minimized oxidation of chlorophyll-a, the primary pigment responsible for the characteristic green color, while auxiliary pigments (chlorophyll-b, carotenoids) showed no significant improvement.

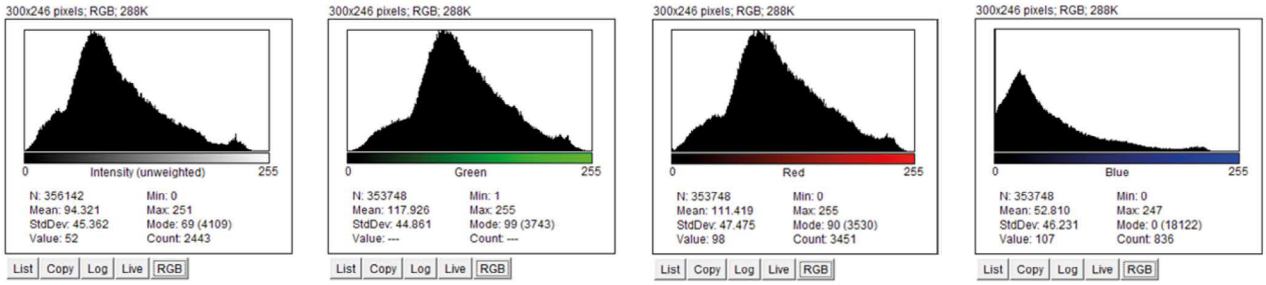
Our findings are consistent with those in [2, 4], both of which emphasized that optimizing the treatment conditions-temperature, solution composition, and immersion time-plays a critical role in preserving chlorophyll-a.



a b c d

Figure 9. Color intensity (a), green (b), red (c), and blue (d) indices of the commercial dehydrated sea grapes Trí Tín and D&T (Image J). The values represent the M ± SD from three independent replicates (n = 3)

Рисунок 9. Интенсивность цвета (a), а также индексы зеленого (b), красного (c) и синего (d) коммерческих образцов высушенного морского винограда (*Caulerpa lentillifera*) брэндов “Trí Tín” и “D&T” (J): среднее значение ± стандартное отклонение (n = 3)



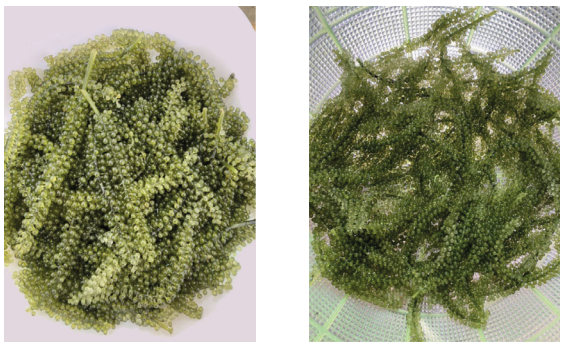
a b c d

Figure 10. Color intensity (a), green (b), red (c), and blue (d) indices of the final product after dehydration and color fixation (Image J). The values represent the M ± SD from three independent replicates (n = 3)

Рисунок 10. Интенсивность цвета (a), а также индексы зеленого (b), красного (c) и синего (d) после процедур сушки и фиксации цвета (J): среднее значение ± стандартное отклонение (n = 3)

From a practical perspective, our results suggest that the final sea grape product may achieve an extended shelf life of 4–6 weeks, a reduction in spoilage rate by approximately 20–25%, and cost savings of 10–15% in total preservation and logistics. These improvements enhance profitability and support compliance with the strict quality standards required by the international markets.

Our study clearly demonstrates the superior effectiveness and high feasibility of the optimized technical solution for dehydration and color fixation of the sea grapes (*C. lentillifera*). Specifically, their structural recovery rate of 90.87% was significantly higher than that of the conventional commercial products (82–85%). Their green index and color intensity of 117.93 and 94.32, respectively, substantially outperformed the current commercial standards of 99.63 and 84.76, respectively. This validated the technical superiority of the optimized process. Figure 11 shows the morphology of the sea grapes before and after processing with no significant changes in freshness and appearance.



a b

Figure 11. Sea grapes before (a) and after (b) being processed under the optimized parameters

Рисунок 11. Морской виноград до (a) и после (b) обработки по оптимизированным параметрам

One of the key results of this study is that we determined the ideal blanching conditions (90°C for 10 s), followed by rapid cooling (10–15°C) to inactivate polyphenol oxidase and peroxidase without significantly damaging the cell structure. Unlike the studies by Goncalves *et al*. [8] on carrots (*Daucus carota* L.) and Satmalee *et al*. [9] on seaweed (*Ulva rigida*), which used longer heat treatments (3–5 min), our study was the first to demonstrate the effectiveness of ultra-short thermal processing on sea grapes. Thus, our results contribute valuable new data to the field of tropical seaweed processing.

Our study also confirmed the effectiveness of the 15% NaCl + 5% sorbitol solution. This combination was optimal due to the biochemical properties of sorbitol, a polyol with multiple hydroxyl groups capable of forming strong and stable hydrogen bonds with intracellular water. When combined with a moderate NaCl concentration (15%), the solution achieves ideal osmotic balance. This balance is strong enough to facilitate reverse osmosis and water removal without causing excessive cellular damage. This maintains intracellular water balance, removes external free water, and preserves essential bound water. As a result, it prevents excessive cell shrinkage and protects chlorophyll-a, a pigment highly vulnerable to dehydration.

Our findings build upon and clarify earlier conclusions from previous studies [2, 4], which lacked detailed explanations of the interaction between sorbitol and NaCl in protecting pigments and cellular structures in sea grapes.

Our experimental product demonstrated significantly better color indices compared to the commercial sea grapes. The main reason for this improvement lies in the synchronized optimization of technical parameters. Notably, the use of high blanching temperature for a very short time (90°C for 10 s) combined with rapid cooling effectively prevented oxidation and degradation of chlorophyll-a, the key cause of discoloration in com-

mercial products. In contrast, commercial methods often use longer blanching times or suboptimal temperatures, leading to severe chlorophyll-a loss and significantly diminished sensory quality.

Despite these promising results, large-scale industrial adoption of this technology still faces several challenges. They include high initial investment in precise temperature control and rapid cooling systems, the need for consistent training of technical staff, and the development of strict quality control systems for raw material sourcing. Enterprises must carefully consider these factors and develop clear management strategies to ensure successful large-scale implementation.

To enhance reliability and practical application, future studies should focus on identifying changes in essential nutrients – such as vitamin A, vitamin C, iodine, and essential fatty acids (EPA, DHA) – under long-term storage conditions. Simulations of real-world transportation and storage conditions are also necessary to assess product stability prior to commercialization.

From an economic perspective, our study holds significant implications for sea grape producers and exporters. A 20–25% reduction in spoilage rates and 10–15% savings in total preservation and logistics costs could lead to a substantial increase of 15–20% in net profit [2, 4]. This not only improves the economic efficiency but also enhances the competitiveness of Vietnamese sea grapes in the demanding international markets such as Japan, South Korea, and Europe, where sensory quality, nutritional value, and food safety are top consumer priorities.

Conclusion

Our study established a comprehensive technical solution for optimizing the dehydration and color fixation of sea grapes (*Caulerpa lentillifera*). The optimal conditions were identified as blanching at 90°C for 10 s, followed by rapid cooling at 10–15°C, and subsequent immersion in a color fixation solution of 15% NaCl and 5% sorbitol for 10–15 min. These conditions effectively protect the cellular structure, inhibit the activity of polyphenol oxidase, and maintain high stability of chlorophyll-a pigment. Compared to the commercial dehydrated sea grape products on the market, our final product showed significant improvements in the green index and color intensity. The application of this optimized process not only extends shelf life, reduces spoilage rates, and lowers preservation costs, but also enables the product to meet the stringent international quality standards. This, in turn, enhances the export potential and global competitiveness of Vietnamese sea grapes.

Contribution

B.T.T. Hien conceptualized and designed the research, defined research objectives, performed data analysis, interpreted results, provided scientific oversight, conducted the majority of analytical experiments, and proofread the manuscript. P.T. Diem, D.V. An, and N.K. Bat contributed to literature review, conducted additional analytical experiments, and participated in manuscript revision.

Conflict of interest

The authors declared no conflict of interest regarding the publication of this manuscript.

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Declaration of AI and AI-assisted technologies

Humanize AI was used in some parts of the manuscript to refine the English expressions and improve fluency. The tool was applied only for language polishing and did not generate or modify the scientific content. All AI-suggested edits were manually reviewed by the authors to ensure the accuracy and integrity of the original ideas. The use of Humanize AI did not affect the key arguments or conclusions of the manuscript.

Критерии авторства

Буи Тхи Тху Хиен разработала концепцию и методологию исследования, сформулировала цели и задачи, выполнила анализ и интерпретацию полученных данных, руководила научной частью проекта, выполнила основную часть аналитических исследований и участвовала в редактировании рукописи. Пхам Тхи Дием, Данг Ван Ан и Нгуен Кхак Бат провели анализ литературных источников, выполнили часть аналитических исследований и участвовали в редактировании рукописи.

Конфликт интересов

Авторы заявляют об отсутствии конфликта интересов, связанных с публикацией данной рукописи.

Благодарности

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Декларация использования ИИ

Авторы заявляют об использовании текстового конвертера “Humanize AI” в целях создания лингвистической аутентичности английского текста. Обработка ни коим образом не затронула научное содержание статьи, а также ключевые аргументы или выводы, а все предложенные ИИ правки проверялись авторами вручную.

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