



(RESEARCH ARTICLE)



Valorization of sea fennel (*Crithmum maritimum* L.) as a natural additive in a "clean label" orange jam: Effects on physicochemical, microbiological, and sensory properties

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International Journal of Science and Research Archive, 2025, 16(02), 1557-1571

Publication history: Received on 22 July 2025; revised on 26 August 2025; accepted on 30 August 2025

Article DOI: <https://doi.org/10.30574/ijrsra.2025.16.2.2505>

Abstract

The rising consumer demand for "Clean Label" products fuels research into natural food additives. Sea fennel (*Crithmum maritimum* L.), a Mediterranean halophyte plant, shows promising potential due to its rich composition of bioactive compounds. This study aims to assess its use as a natural additive to enhance the stability and quality of orange jam. Six orange jam formulations were prepared: a control (C), a control with citric acid (CAC), and four with different percentages of sea fennel powder (0.5%, 1%, 1.5%, and 2%). Physicochemical properties (Brix, pH, titratable acidity, water activity –Aw, and colometry), microbiological stability, and sensory characteristics were evaluated over a 60-day storage period at 20°C and 37°C. The addition of sea fennel significantly lowered the initial pH (from 3.78 to 3.71) and water activity (from 0.89 to 0.77), which was confirmed to improve microbiological stability, with all samples remaining compliant with standards after 60 days. Increasing sea fennel content showed a notable color shift toward greenish hues. Sensory analysis indicated that the formulation with 0.5% sea fennel was most preferred by consumers, showing no significant difference in taste or texture compared to the control jam. Sea fennel can be used at a 0.5% concentration as a natural additive to create a "Clean Label," reduced-sugar orange jam with improved stability and high consumer acceptance.

Keywords: *Crithmum maritimum* L.; Sea Fennel; Orange Jam; Natural Additive; Clean Label; Physicochemical Properties; Storage Stability; Sensory Analysis

1 Introduction

The rising prevalence of lifestyle-related diseases such as obesity, type 2 diabetes, and cardiovascular conditions has increased consumer demand for healthier food choices with lower sugar content [1,2]. Fruit jams, traditionally made with high sugar levels to ensure microbial safety and good texture, are especially impacted by this trend. While reducing sugar aligns with current nutritional guidelines, it affects product stability by changing water activity, pH, gel formation, and vulnerability to microbial spoilage [3,4]. Therefore, there is a strong need to find natural ingredients that can replace sugar's technological functions while boosting nutritional value.

In parallel, the clean label concept has emerged as a dominant trend in the food industry. Clean label refers to minimally processed products, free from artificial additives, and characterized by transparent labeling with short and recognizable ingredient lists [5]. Consumers increasingly associate clean label products with health, naturalness, and authenticity, leading manufacturers to substitute synthetic preservatives and colorants with natural alternatives [6]. Thus,

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developing clean label formulations requires identifying multifunctional natural ingredients that can simultaneously improve stability, safety, and nutritional value while meeting expectations for transparency.

In this context, *Crithmum maritimum* L. (sea fennel), a halophytic species belonging to the Apiaceae family, emerges as a promising candidate. Native to Mediterranean coasts, sea fennel has a long history of culinary and medicinal use. It is rich in polyphenols, flavonoids, essential oils, and vitamin C, which provide potent antioxidant, antimicrobial, and preservative properties [7-9]. Recent studies have highlighted its ability to inhibit oxidative processes, reduce microbial growth, and improve sensory complexity in food formulations [10,11]. Incorporating sea fennel powder into reduced-sugar jams may therefore serve as a sustainable and natural approach to counteract the negative effects of sugar reduction on physicochemical and microbiological stability.

Beyond technological benefits, sea fennel also supports the development of functional foods, which are increasingly valued for their health benefits. Functional foods offer extra physiological advantages beyond basic nutrition, often enriched with bioactive compounds like polyphenols, carotenoids, or dietary fibers [12].

Sea fennel is especially rich in these compounds, and including it in fruit-based products could boost antioxidant capacity and mineral intake while promoting the clean label movement that emphasizes transparency, minimal processing, and replacing synthetic additives with natural options [13,14].

Based on these considerations, the current study aimed to valorize *C. maritimum* as a natural additive in reduced-sugar orange jam. The effects of sea fennel incorporation were evaluated on physicochemical properties during storage (20 and 37°C over 60 days), stability under accelerated aging conditions (40–60°C over 28 days), and color changes.

Lastly, Sensory analysis was conducted to identify the most acceptable formulation from a consumer standpoint. This work offers new insights into the potential use of sea fennel to balance sugar reduction, product stability, and consumer health preferences in developing clean-label fruit jams.

2 Materials and Methods

2.1 Plant Material

Plant materials were washed, cleaned, and divided into treatment groups. Fresh oranges (*Citrus sinensis* L., var. Maltaise) were sourced locally in Tunisia, selected for uniformity in size, color, and absence of damage. *C. maritimum* was wild-harvested from Cap Negro (Nefza, Tunisia). The aerial parts were dehydrated at 45 °C for 48 hours using a food dehydrator—a temperature proven to preserve volatile and essential oil bioactives in halophytic plants such as *C. maritimum* [15]—and confirmed in our own previous study to maximize essential oil yield and antioxidant retention [16]. The dried material was ground into a fine powder (< 500 µm). Other ingredients (sugar, citric acid) were food-grade and locally sourced.

2.2 Jam Formulation and Preparation

Six different jam formulations were prepared. A low-sugar base was created using a fruit-to-sugar ratio 2:1 (1 kg of orange pulp to 500 g of sugar). The formulations were as follows

- **Control (C):** Orange jam without any additives.
- **Control + CA:** Orange jam with 0.21% (w/w) citric acid.
- **SF 0.5%:** Orange jam with 0.5% (w/w) *C. maritimum* powder.
- **SF 1.0%:** Orange jam with 1.0% (w/w) *C. maritimum* powder.
- **SF 1.5%:** Orange jam with 1.5% (w/w) *C. maritimum* powder.
- **SF 2.0%:** Orange jam with 2.0% (w/w) *C. maritimum* powder.

The jam preparation followed a standardized protocol. Oranges were washed, and the flavedo (outer peel) was carefully removed to avoid bitterness, while retaining the pectin-rich albedo. The pulp was cut into small pieces, and the seeds were discarded. The orange pieces were mixed with sugar and cooked in a granite pot over low heat for approximately 40 minutes, with constant stirring. Towards the end of the cooking process, an immersion blender was used to achieve a homogeneous consistency. The corresponding amount of *C. maritimum* powder or citric acid was added and thoroughly mixed for the supplemented formulations. The hot jam was immediately filled into pre-sterilized glass jars (100 g), then hermetically sealed. The filled jars were pasteurized in a water bath at 65 °C for 30 minutes and cooled to room temperature.

2.3 Physicochemical Analyses

All physicochemical analyses were performed in triplicate on the day of production (day 0) and at regular intervals during the storage studies.

- **pH:** The pH was measured directly on the jam samples using a calibrated digital pH meter (METTLER TOLEDO), according to ISO 1842:1991 [17].
- **Titrateable Acidity (TA):** The Titrateable Acidity was determined according to the standard method (NF V 05-101) [18]. A 25 g jam sample was homogenized in 50 mL of distilled water, brought to a final volume of 250 mL, and filtered. A 25 mL aliquot of the filtrate was titrated with 0.1 N NaOH solution using phenolphthalein as an indicator. TA was expressed as milliequivalents per 100 g of product.
- **Soluble Solids Content (°Brix):** The soluble solids content was measured at 20 °C using a digital refractometer (Anton Paar), according to the standard method NF V05-109 [19].
- **Water Activity (aw):** Water activity was measured at 25 °C using a water activity meter (ROTRONIC) following AOAC standard procedures [20].
- **Color Measurement:** The color of the jam samples was measured using a KONICA MINOLTA colorimeter according to Minolta (1994) and ASTM E308-08 [21,22]. The results were expressed in the CIE Lab* color space, where L* represents lightness (0=black, 100=white), a* represents the green (-) to red (+) axis, and b* represents the blue (-) to yellow (+) axis.

2.4 Storage and Stability Studies

To evaluate the effect of *C. maritimum* on the stability of the jam, two storage studies were conducted

- **Long-Time Storage Study:** The jam samples were stored for 60 days in controlled environments at two different temperatures: ambient (20 ± 2 °C) and elevated (37 ± 2 °C). Physicochemical parameters (pH, TA, °Brix, aw, and color) were monitored at day 0, 15, 30, 45, and 60 [23].
- **Accelerated Shelf-Life Study:** An accelerated aging test assessed long-term stability. Samples were stored at three elevated temperatures (40, 50, and 60 °C) for 28 days. Physicochemical properties were monitored weekly to model degradation kinetics [24].

2.5 Microbiological Analysis

The microbiological quality of the jam samples was assessed after 60 days of storage at 20 °C. Total aerobic mesophilic flora (FMAT) was enumerated on Plate Count Agar (PCA) after incubation at 30 °C for 72 hours [25,26]. Yeast and mold counts were determined on Sabouraud Dextrose Agar after incubation at 25 °C for 3-5 days. Results were expressed as colony-forming units per gram (CFU/g) [27].

2.6 Sensory Analysis

The sensory acceptability of the jam formulations was evaluated through two distinct tests. First, a descriptive analysis was conducted with 10 trained tasters to profile the sensory attributes (color, odor, flavor, texture, bitterness) of all formulations. Based on these results, the most promising formulation (SF 0.5%) and the control (C) were selected for a consumer hedonic test. A panel of 50 untrained consumers evaluated the overall acceptability of the two samples based on color, odor, texture, and taste, using a 5-point hedonic scale (1 = dislike immensely, 5 = like extremely) [28,29].

2.7 Statistical Analysis

All experiments were conducted in triplicate, and results are reported as mean \pm standard deviation (SD). Statistical analyses were performed to determine the significance of differences among formulations and storage conditions. At Day 0, the initial physicochemical and colorimetric properties of the six jam formulations were compared using one-way analysis of variance (ANOVA). When significant effects were detected, Tukey's Honestly Significant Difference (HSD) post-hoc test was applied to identify pairwise differences between formulations.

For the storage stability studies (accelerated and long-term), two-way ANOVA was employed with Formulation and Storage Day as main factors, as well as their interaction (Formulation \times Day). Sensory data from the consumer hedonic test, comparing the control and SF 0.5% formulations, were analyzed using an independent-samples t-test. A significance threshold of $p < 0.05$ was used for all analyses.

Data processing and visualization were performed using Python (version 3.11). The Pandas (v2.2) library was used for data manipulation, and Matplotlib (v3.8) and Seaborn (v0.13) were employed for plotting.

3 Results

3.1 Initial Physicochemical and Colorimetric Properties of Jam Formulations

To establish a baseline, the six orange jam formulations were evaluated immediately after preparation (Day 0). The one-way ANOVA revealed significant differences ($p < 0.001$) among all measured parameters. The most relevant pairwise comparisons are summarized in Table 1.

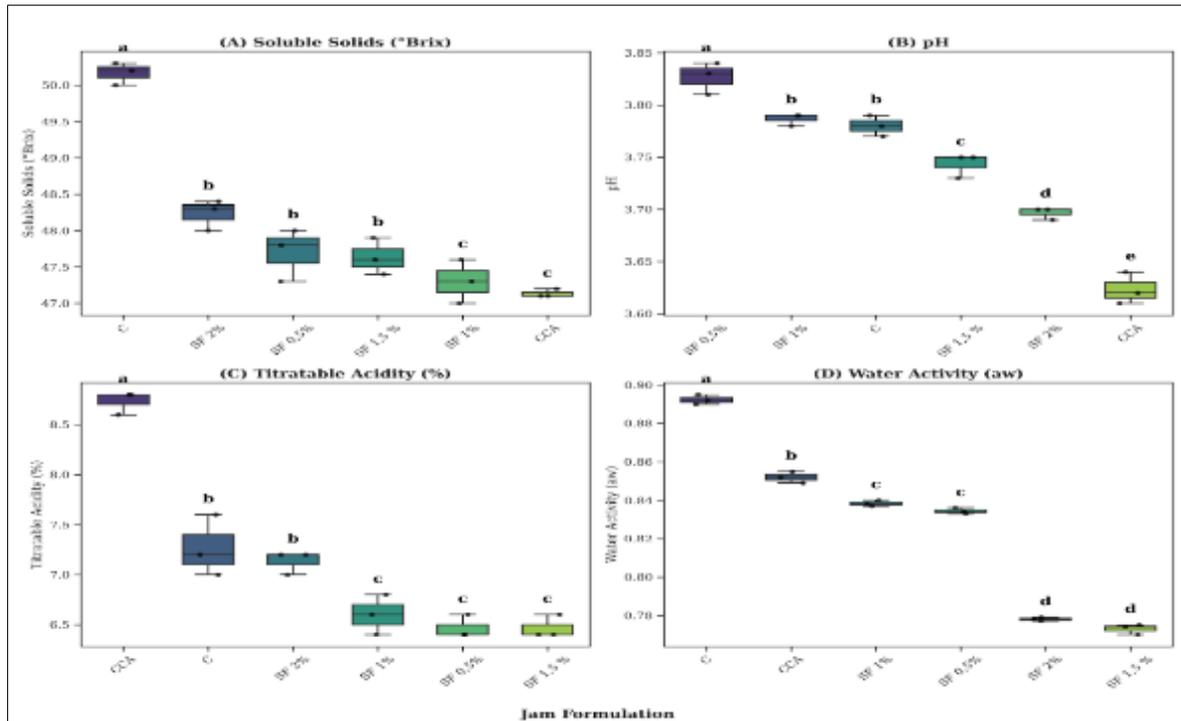
Table 1 Summary of significant pairwise comparisons for physicochemical and colorimetric parameters at Day 0 based on Tukey's HSD post-hoc test ($p < 0.05$)

| Parameter | Group 1 | Group 2 | Mean Difference | p-adj |
|-----------|---------|---------|-----------------|--------|
| Brix | C | CCA | -3.03 | <0.001 |
| | C | SF 2% | -1.93 | <0.001 |
| | CCA | SF 2% | 1.10 | 0.001 |
| pH | C | CCA | -0.16 | <0.001 |
| | CCA | SF 0.5% | 0.20 | <0.001 |
| | SF 0.5% | SF 2% | -0.13 | <0.001 |
| TA | C | CCA | 1.47 | <0.001 |
| | CCA | SF 0.5% | -2.27 | <0.001 |
| | SF 0.5% | SF 2% | 0.67 | 0.006 |
| aw | C | SF 1.5% | -0.12 | <0.001 |
| | CCA | SF 1.5% | -0.08 | <0.001 |
| | SF 0.5% | SF 1.5% | -0.06 | <0.001 |
| L* | C | SF 1.5% | -9.79 | <0.001 |
| | CCA | SF 1.5% | -15.81 | <0.001 |
| a* | C | SF 2% | -2.11 | <0.001 |
| | CCA | SF 2% | -2.58 | <0.001 |
| | SF 0.5% | SF 2% | -0.87 | <0.001 |
| b* | C | SF 2% | -13.33 | <0.001 |
| | CCA | SF 2% | -19.89 | <0.001 |
| | SF 0.5% | SF 2% | -7.98 | <0.001 |

(Note: Table shows selected significant comparisons for brevity; refer to full statistical output for all pairs.)

Compared to the control (C), soluble solids ($^{\circ}$ Brix) were lower in both the citric-acid control (CCA; $\Delta = -3.03$, $p < 0.001$) and SF 2% ($\Delta = -1.93$, $p < 0.001$); CCA also differed from SF 2% ($\Delta = +1.10$, $p = 0.001$). In terms of acidity, CCA vs C showed a lower pH ($\Delta = -0.16$, $p < 0.001$) and higher titratable acidity (TA; $\Delta = +1.47$ meq/100 g, $p < 0.001$). Within the SF series, pH decreased with increasing dose (e.g., SF 0.5% vs SF 2%: $\Delta = -0.13$, $p < 0.001$), and TA increased (SF 0.5% vs SF 2%: $\Delta = +0.67$ meq/100 g, $p = 0.006$). Water activity (a_w) was also formulation-dependent, showing lower values in SF 1.5% compared to C ($\Delta = -0.12$, $p < 0.001$) and CCA ($\Delta = -0.08$, $p < 0.001$); within the SF series, SF 1.5% had a lower water activity than SF 0.5% ($\Delta = -0.06$, $p < 0.001$). Colorimetric differences were notable: lightness L^* decreased in SF 1.5% compared to C ($\Delta = -9.79$, $p < 0.001$) and CCA ($\Delta = -15.81$, $p < 0.001$). Redness a^* and yellowness b^* were both lower in SF 2% compared with C (a^* : $\Delta = -2.11$; b^* : $\Delta = -13.33$; both $p < 0.001$) and CCA (a^* : $\Delta = -2.58$; b^* : $\Delta = -19.89$; both $p < 0.001$).

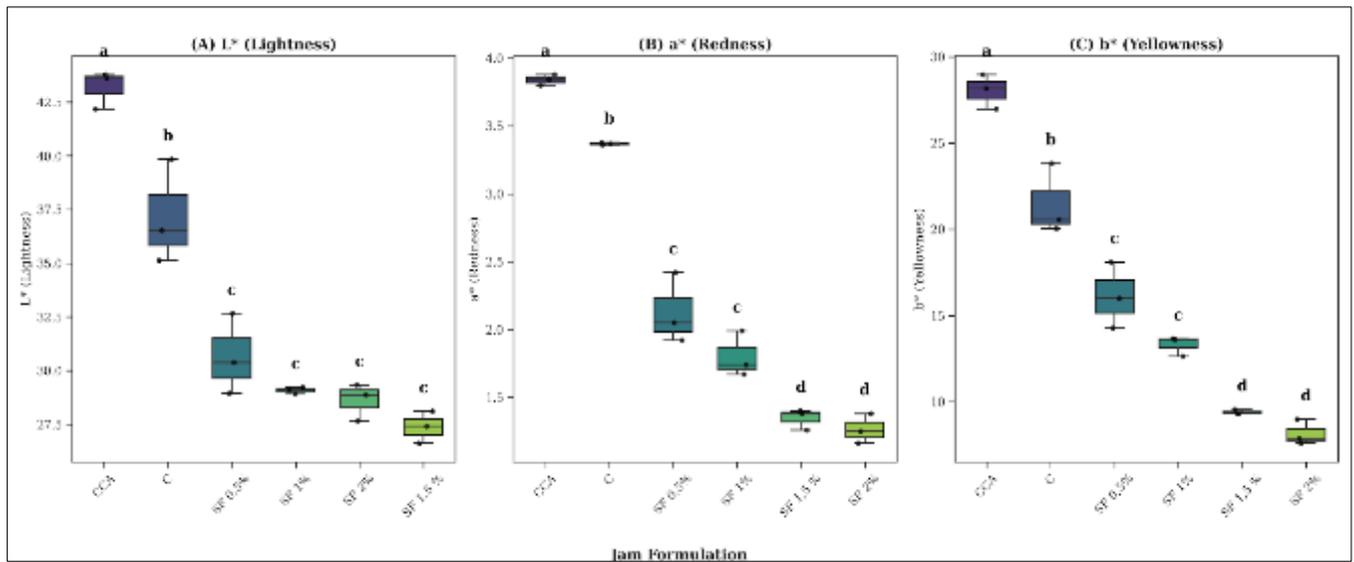
To compare these baseline differences on the same scale, Figure 1 shows $^{\circ}$ Brix, pH, TA, and a_w by formulation; Figure 2 presents CIELab coordinates.



(A) Soluble Solids (°Brix); (B) pH; (C) Titratable Acidity (TA); (D) Water Activity (aw). Treatments: C (Control), CCA (Control with Citric Acid), SF 0.5% to SF 2% (formulations with 0.5% to 2% sea fennel powder). Different letters above the bars indicate statistically significant differences between formulations according to Tukey's HSD test ($p < 0.05$).

Figure 1 Physicochemical properties of different orange jam formulations at Day 0

At Day 0, C displayed the highest °Brix; CCA showed the lowest pH and highest TA. All SF-fortified jams exhibited lower aw than C, consistent with a more constrained water availability at the formulation scale.



(A) L* coordinate (Lightness); (B) a* coordinate (Redness); (C) b* coordinate (Yellowness). Treatments: C (Control), CCA (Control with Citric Acid), SF 0.5% to SF 2% (formulations with 0.5% to 2% sea fennel powder). Different letters above the bars indicate statistically significant differences between formulations according to Tukey's HSD test ($p < 0.05$).

Figure 2 Colorimetric properties of different orange jam formulations at Day 0

SF levels decreased L^* , a^* , and b^* compared to both Controls. The shift became more pronounced with higher SF concentrations, resulting in darker, less red, and less yellow jams.

3.2 Stability During Accelerated Shelf-Life Storage

To investigate the impact of recipe and temperature on jam stability, all formulations were stored under accelerated conditions (40, 50, and 60 °C) for 28 days. A two-way ANOVA was performed for each parameter, with *Recipe*, *Day*, and their interaction (*Recipe* × *Day*) as factors. The results, summarized in **Table 2**, show that all effects were highly significant ($p < 0.001$), confirming that both formulation and storage duration and their interaction influenced the physicochemical and colorimetric trajectories.

Table 2 Summary of p-values from two-way ANOVA (Recipe x Day) for parameters during storage at 40, 50, and 60°C

| Parameter | Source of Variation | p-value (40°C) | p-value (50°C) | p-value (60°C) |
|-----------|-------------------------|----------------|----------------|----------------|
| °Brix | Recipe | <0.001 | <0.001 | <0.001 |
| | Day | <0.001 | <0.001 | <0.001 |
| | Recipe:Day Interaction | <0.001 | <0.001 | <0.001 |
| pH | Recipe | <0.001 | <0.001 | <0.001 |
| | Day | <0.001 | <0.001 | <0.001 |
| | Recipe: Day Interaction | <0.001 | <0.001 | <0.001 |
| TA | Recipe | <0.001 | <0.001 | <0.001 |
| | Day | <0.001 | <0.001 | <0.001 |
| | Recipe: Day Interaction | <0.001 | <0.001 | <0.001 |
| L^* | Recipe | <0.001 | <0.001 | <0.001 |
| | Day | <0.001 | <0.001 | <0.001 |
| | Recipe: Day Interaction | <0.001 | <0.001 | <0.001 |
| a^* | Recipe | <0.001 | <0.001 | <0.001 |
| | Day | <0.001 | <0.001 | <0.001 |
| | Recipe: Day Interaction | <0.001 | <0.001 | <0.001 |
| b^* | Recipe | <0.001 | <0.001 | <0.001 |
| | Day | <0.001 | <0.001 | <0.001 |
| | Recipe: Day Interaction | <0.001 | <0.001 | <0.001 |

All effects are statistically significant.

Across all storage conditions, °Brix, pH, TA, and color parameters evolved differently depending on the formulation. The significant *Recipe* × *Day* interactions demonstrate that stability patterns varied by formulation over time, indicating that the effect of sea fennel enrichment was temperature-dependent.

To better illustrate these dynamics, Figure 3 presents the time-course of the main physicochemical properties (°Brix, pH, TA) across the three storage temperatures.

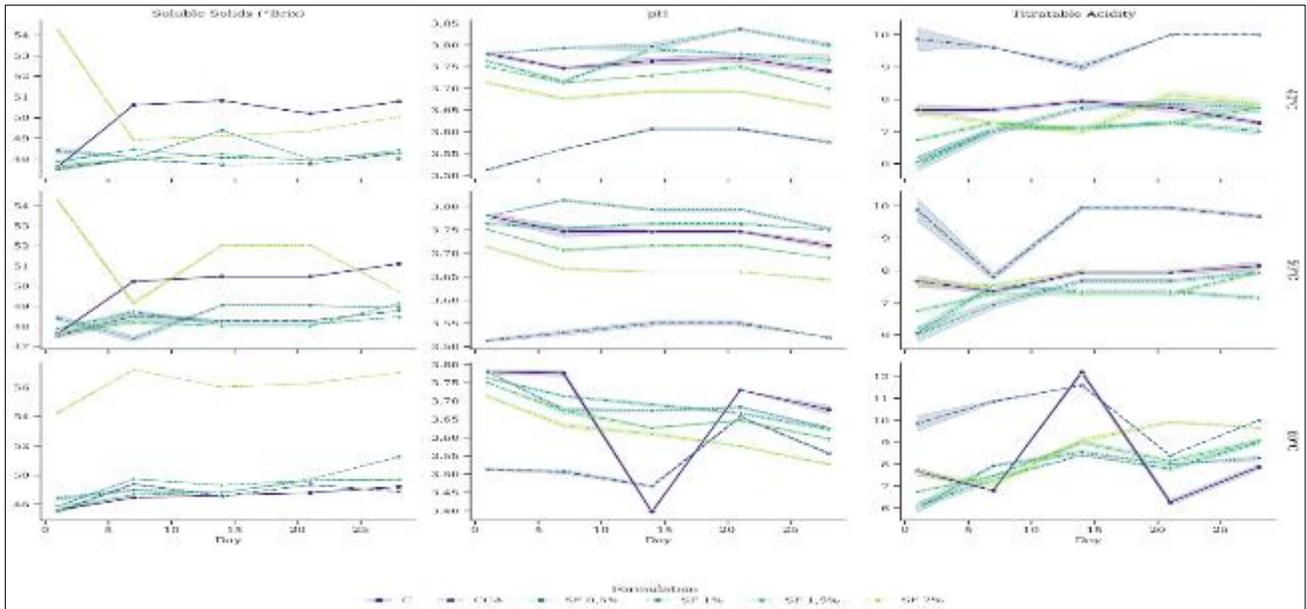


Figure 3 Evolution of physicochemical properties in orange jam formulations during 28 days of accelerated storage

At 40 °C, pH remained relatively stable for the control (C), while formulations with citric acid (CCA) or sea fennel experienced slightly more fluctuations. At 50 °C, CCA had the most stable pH profile, whereas SF formulations tended to decrease slightly over time. At 60 °C, CCA again showed the smallest pH decrease, while SF jams experienced slightly larger shifts, though they remained limited.

Titratable acidity (TA) showed temperature-specific stability patterns. At 40 °C, the CCA jam kept the most stable TA values, while SF formulations gradually increased. At 50 °C, SF 2% was the most stable, with minimal changes over 28 days. At 60 °C, the control (C) was the most stable, with CCA and SF samples showing slightly larger variations.

Soluble solids content (°Brix) generally remained stable across all conditions. The most consistent results were SF 1% at 40 and 50 °C, showing only minor declines compared to other formulations. At 60 °C, the differences between recipes diminished, with all formulations experiencing a slight but similar reduction.

Color stability (Figure 4) was further assessed by monitoring L*, a*, and b* coordinates and the overall color difference (ΔE).

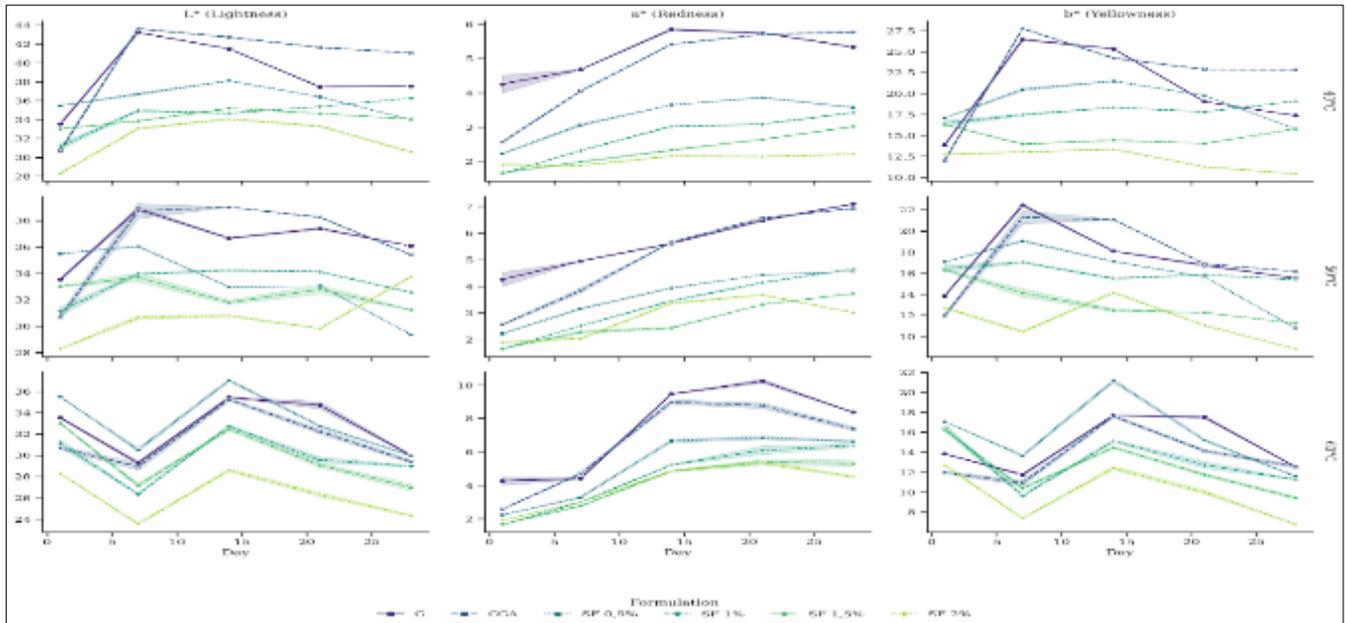


Figure 4 Evolution of colorimetric properties in orange jam formulations during 28 days of accelerated storage

At 40°C, SF formulations showed better color stability than controls, with the lowest ΔE observed in SF 1.5% ($\Delta E = 1.78 \pm 0.07$), followed by SF 0.5% ($\Delta E = 2.39 \pm 0.02$). The control (C) and especially CCA had higher ΔE values (5.45 ± 0.21 and 15.36 ± 0.45 , respectively), indicating more significant color degradation.

At 50 °C, SF 1% exhibited the best color stability ($\Delta E = 3.56 \pm 0.08$), followed by the control ($\Delta E = 4.17 \pm 0.39$). Other SF formulations showed intermediate values, while CCA and SF 0.5% degraded more significantly ($\Delta E = 7.66 \pm 0.39$ and 9.06 ± 0.04 , respectively).

At 60 °C, the control and CCA showed the lowest ΔE values (5.58 ± 0.31 and 5.07 ± 0.13 , respectively), indicating better stability under harsher conditions. SF 1% and SF 2% were close behind ($\Delta E \approx 7.3$ – 7.6), while SF 0.5% and SF 1.5% showed the highest instability ($\Delta E \approx 8.9$ – 9.8).

These results show that sea fennel supplementation affected physicochemical and color stability during accelerated storage. Intermediate concentrations (0.5–1.5%) enhanced color stability at moderate temperatures (40–50 °C), while control and CCA performed better at the highest temperature (60 °C).

3.3 Stability During Long-Time Storage

The jam formulations' long-term stability was evaluated over a 60-day storage period under long-time conditions: 20°C (ambient) and 37°C (abuse temperature) to validate the accelerated tests' findings.

The statistical significance of the Recipe, Day, and their interaction was assessed for each temperature, with the results presented in Table 3.

Table 3 Summary of p-values from two-way ANOVA (Recipe x Day) for parameters during long-time storage at 20°C and 37°C

| Parameter | Source of Variation | p-value (20°C) | p-value (37°C) |
|-----------|-------------------------|----------------|----------------|
| | Recipe | <0.001 | <0.001 |
| °Brix | Day | <0.001 | <0.001 |
| | Recipe: Day Interaction | <0.001 | <0.001 |
| | Recipe | <0.001 | <0.001 |
| pH | Day | <0.001 | <0.001 |
| | Recipe: Day Interaction | <0.001 | <0.001 |
| | Recipe | <0.001 | <0.001 |
| TA | Day | <0.001 | <0.001 |
| | Recipe: Day Interaction | <0.001 | <0.001 |
| | Recipe | <0.001 | <0.001 |
| aw | Day | <0.001 | <0.001 |
| | Recipe: Day Interaction | <0.001 | <0.001 |
| | Recipe | <0.001 | <0.001 |
| L* | Day | <0.001 | <0.001 |
| | Recipe: Day Interaction | <0.001 | <0.001 |
| | Recipe | <0.001 | <0.001 |
| a* | Day | <0.001 | <0.001 |
| | Recipe: Day Interaction | <0.001 | <0.001 |
| | Recipe | <0.001 | <0.001 |
| b* | Day | <0.001 | <0.001 |
| | Recipe: Day Interaction | <0.001 | <0.001 |

The statistical analysis presented in Table 3 confirms that the Recipe: Day interaction was significant ($p < 0.05$) for all physicochemical and colorimetric parameters under ambient and abuse temperature conditions. This finding is important because it shows that the recipes behaved differently over the 60-day storage period, supporting the results of the accelerated shelf-life study. The significant interaction provides a statistical basis for concluding that the sea fennel additive has a measurable impact on the long-term stability of the jam.

The evolution of these properties is visually detailed in Figure 5 for physicochemical parameters and Figure 6 for colorimetric parameters.

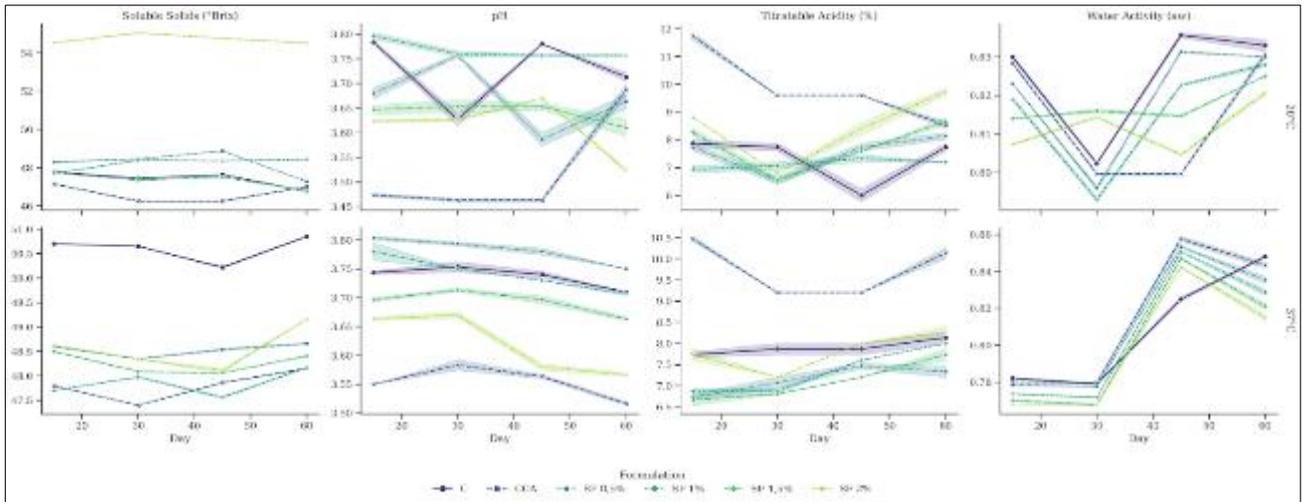


Figure 5 Evolution of physicochemical properties in orange jam formulations during 60 days of long-time storage, faceted by temperature

The data in Figure 5 shows the long-term evolution of the jams. The abuse temperature of 37°C induced more pronounced changes. For instance, after 60 days at 37°C, the pH of the control jam (C) decreased from approximately 3.78 to 3.73. In contrast, the SF 2% formulation maintained a more stable pH, ending at roughly 3.71 after starting at about 3.70, indicating better acid stability over time. Similarly, the control jam's water activity (a_w) showed a more significant decrease than the SF formulations, which remained more stable throughout the 60-day period.

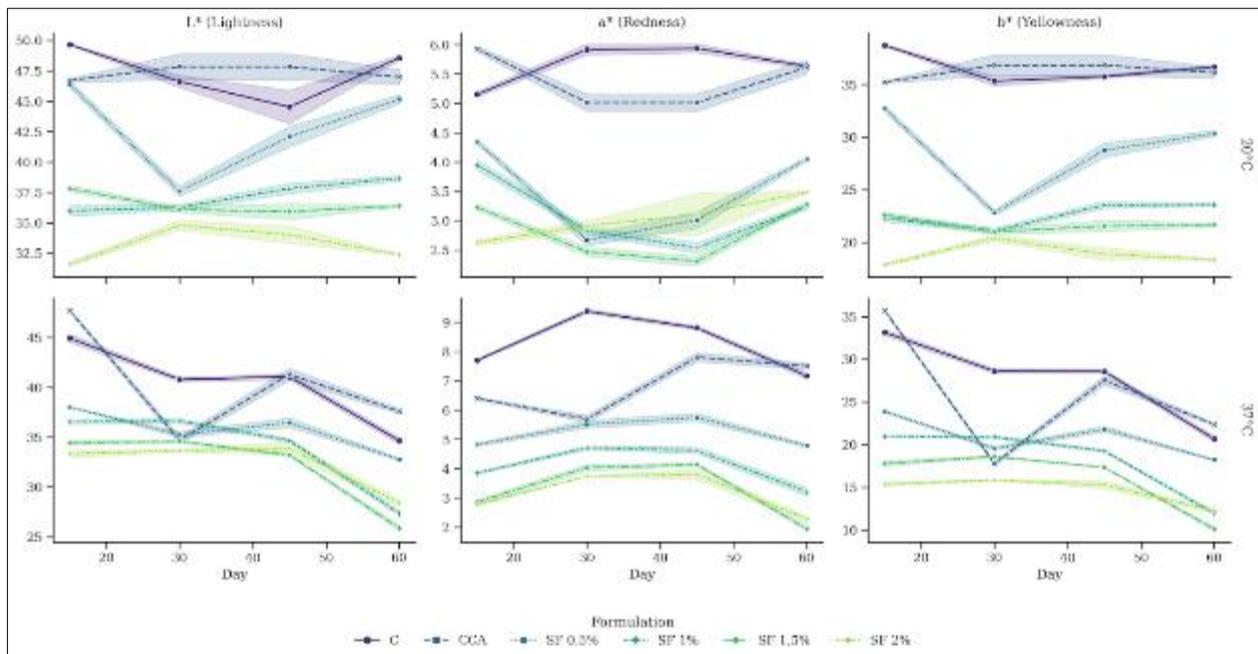


Figure 6 Evolution of colorimetric properties in orange jam formulations during 60 days of long-time storage, faceted by temperature

The color changes over 60 days, shown in Figure 6, confirm the trends seen in the accelerated study. At 37°C, the control jam (C) showed a noticeable loss in lightness (L^*), decreasing from about 37.2 to 35.0. Although the SF 2% jam was naturally darker (initial $L^* \approx 24.9$), its value stayed remarkably stable, ending at around 24.5. Compared to the control, this small change suggests a strong resistance to browning during realistic storage conditions. This long-term color stability is an important finding, highlighting the potential of sea fennel as a natural additive to help maintain the visual quality of orange jam throughout its shelf life.

3.4 Microbiological Analysis

To assess the microbiological stability of the jam formulations, total aerobic mesophilic flora (FMAT) and yeast and mold counts were determined after a 60-day storage period at an ambient temperature of 20°C. The results, presented in Table 4, indicate a high level of microbiological quality across all samples.

Table 4 Microbiological quality of jam formulations after 60 days of storage

| Formulation | Yeast and Molds (UFC/g) | Total Mesophilic Flora (UFC/g) |
|--------------|-------------------------|--------------------------------|
| Control | < 10 | < 10 |
| Control + CA | 0 | 0 |
| SF 0.5% | < 10 | < 10 |
| SF 1% | < 10 | 2×10^2 |
| SF 1.5% | < 10 | < 10 |
| SF 2% | 2×10^2 | < 10 |

All formulations, including the control and those fortified with sea fennel, complied with established food safety standards. The FMAT counts were well below the threshold of 10^4 UFC/g specified by Tunisian standard NT 48.33 (2003). Similarly, yeast and mold counts were significantly lower than the maximum limit of 10^2 - 10^3 UFC/g set by the French norm NF V08-059 (1995).

3.5 Sensory Analysis

3.5.1 Descriptive Sensory Profiling

A descriptive analysis was first conducted with a panel of 10 trained tasters to create a detailed sensory profile for all six jam formulations. The results of the one-way ANOVA, visualized in the spider web chart (Figure 7), revealed statistically significant differences ($p < 0.05$) among the recipes for the attributes of color, odor, flavor, and overall appreciation.

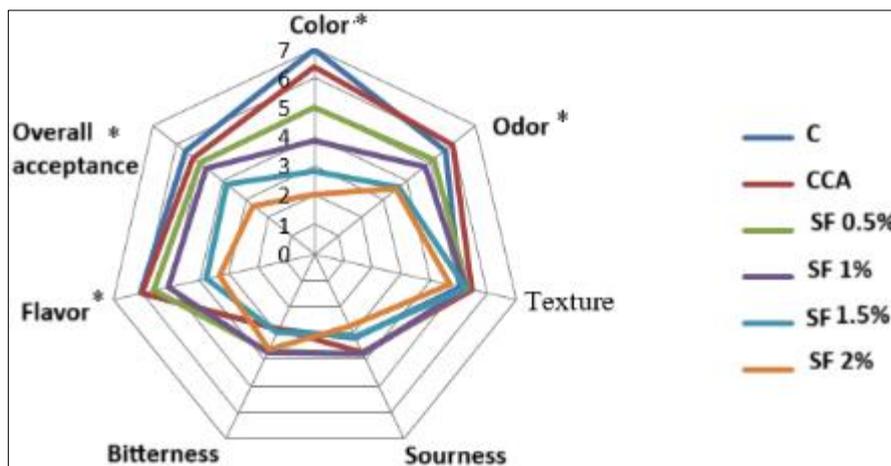


Figure 7 Descriptive sensory profiles of the six orange jam formulations as evaluated by a trained panel (n=10), Asterisks indicate attributes with statistically significant differences ($p < 0.05$) among formulations

The control (C) and the SF 0.5% formulations were the most favored by the trained panel, receiving the highest scores for flavor and overall liking, with average scores between 5 and 7. In contrast, the formulation with the highest sea fennel concentration (SF 2%) was the least preferred. Importantly, no significant differences were found in texture, acid, or bitter taste, indicating that adding sea fennel at these levels did not negatively affect the jam's fundamental mouthfeel. Based on these profiles, the control and SF 0.5% formulations were chosen for the following consumer acceptability test.

3.5.2 Consumer Hedonic Test

A hedonic test was performed with a panel of 50 untrained consumers to evaluate the overall acceptability of the two finalist formulations: the control (C) and SF 0.5%. Consumers rated the jams for color, odor, texture, and taste on a 5-point scale (Table 5).

Table 5 Hedonic scores for Control (C) and 0.5% Sea Fennel (SF 0.5%) jam formulations evaluated by a consumer panel (n=50)

| Formulation | Color | Odor | Texture | Taste |
|-------------|--------------|-------------|-------------|-------------|
| Control (C) | 2.07 ± 0.71* | 2.16 ± 0.81 | 2.13 ± 0.75 | 2.22 ± 0.97 |
| SF 0.5% | 2.50 ± 0.91* | 2.31 ± 0.96 | 2.29 ± 1.02 | 2.25 ± 1.02 |

*An asterisk indicates a significant difference between formulations within the same column ($p < 0.05$). Scores are on a 5-point hedonic scale.

The results, summarized in Table 5, showed no significant statistical difference ($p > 0.05$) between the control and the SF 0.5% jam for the key attributes of odor, texture, and taste.

Interestingly, the analysis revealed a statistically significant difference ($p < 0.05$) for color, with consumers giving a higher score to the SF 0.5% jam (2.50 ± 0.91) than the control jam (2.07 ± 0.71).

4 Discussion

This study aimed to evaluate the potential of sea fennel (*Crithmum maritimum* L.) powder as a natural, multifunctional additive in a "clean label" orange jam. The results demonstrate that incorporating sea fennel, particularly at a concentration of 0.5%, not only preserved but also enhanced several key quality attributes of the final product, thus aligning with the current consumer demand for natural, functional, and healthier foods [30]. Importantly, this outcome corresponds to the technological objective of the study, since the sugar content in the jam was deliberately reduced. Sucrose is traditionally used for sweetness and as a major stabilizer, lowering water activity, controlling microbial growth, and contributing to gel formation in jams and fruit preserves [31,32]. Therefore, successfully stabilizing the reduced-sugar formulations by sea fennel addition confirms its role as an adequate natural substitute for part of the technological functions usually provided by sugar [33].

A primary outcome was the significant impact of sea fennel on the jam's physicochemical properties, which are essential for stability and shelf-life. The observed decrease in pH and the corresponding increase in titratable acidity at higher concentrations of sea fennel powder can be attributed to the intrinsic organic acids naturally present in the plant material [34]. This acidifying effect is highly beneficial, as a lower pH constitutes a critical barrier to microbial growth in fruit preserves [35]. Additionally, the reduction in water activity (a_w) observed with sea fennel incorporation can be explained by the water-binding capacity of its components, particularly dietary fibers, which immobilize free water [36]. The combined effects of low pH and reduced a_w explain the excellent microbiological stability observed in all fortified samples after 60 days of storage, thereby confirming their safety and quality [37]. Comparable results were reported in jams enriched with basil or thyme powders, where phenolic-rich plant matrices reduced water activity and extended microbiological stability [38].

Colorimetric analyses revealed that sea fennel addition significantly altered jam appearance, decreasing lightness (L^*) and shifting the product toward darker, greenish hues due to chlorophylls and other pigments in the powder [39]. While such changes can potentially challenge consumer acceptance, the sensory results indicated that moderate concentrations (0.5–1.0%) maintained acceptable visual quality. More importantly, these intermediate levels demonstrated a protective effect on color stability during accelerated storage, particularly at 40 °C. This stability is most likely related to the presence of polyphenols and vitamin C in *C. maritimum*, which can inhibit enzymatic and non-enzymatic browning reactions [40]. Similar protective effects on pigment stability have been reported in hibiscus-fortified jams, where anthocyanins contributed to delayed browning [41], and in green tea-enriched jams, where catechins reduced color loss during storage [42].

From a consumer standpoint, sensory acceptability represents the ultimate validation of a new formulation. The descriptive sensory analysis clearly showed that higher concentrations of sea fennel ($\geq 1.5\%$) were less appreciated, mainly due to stronger herbal flavor and darker coloration. However, the hedonic test confirmed the 0.5% formulation was highly successful. Untrained consumers perceived no significant differences in taste, odor, or texture between the sea fennel jam and the control, yet they rated the color of the 0.5% jam significantly higher [43]. This indicates that the

subtle greenish hue imparted by low-dose sea fennel was positively perceived, adding a natural uniqueness to the product. Comparable results have been reported with rosemary and moringa leaf powders in fruit preserves, where low incorporation levels enhanced consumer acceptance, while higher concentrations negatively impacted taste and appearance [44,45].

These findings confirm that *C. maritimum* powder at 0.5% constitutes the optimal balance between technological functionality, nutritional enhancement, and consumer satisfaction. It successfully compensates for the reduced stabilizing role of sugar [46], improves physicochemical and microbiological stability, preserves sensory quality, and supports the development of innovative clean-label products—this positions sea fennel as a promising additive in the growing category of functional fruit-based foods.

5 Conclusion

This study highlights the potential of sea fennel (*Crithmum maritimum* L.) powder as a multifunctional ingredient for clean-label foods. Beyond its demonstrated ability to improve microbiological stability and provide antioxidant protection, its incorporation revealed a specific challenge related to color, with a shift toward greenish tones. Rather than being a limitation, this characteristic suggests a strategic opportunity: sea fennel powder could be preferentially used in dark-colored matrices (e.g., chocolate products, berry-based jams, sauces, etc.), where the pigments would blend harmoniously instead of contrasting negatively.

Looking forward, the versatility of *C. maritimum* opens perspectives for its integration into diverse food systems, not only to enhance shelf-life but also to enrich nutritional value and support natural preservation. Exploring its application in dairy alternatives, savory spreads, or functional bakery products could further expand its role as a sustainable additive, bridging technological functionality with consumer expectations for healthier and visually appealing foods.

Compliance with ethical standards

Acknowledgments

This work is part of the PhD research in Agricultural and environmental sciences and technologies at the National Institute of Agronomy of Tunisia (INAT).

Disclosure of conflict of interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization: L.N., S.J., Data, Investigation, Sampling and Formulation L.N., F. M., F.A., S.K., Statistics L.N., S.J., writing: L. N; Supervision, A.K. All authors have read and agreed to the published version of the manuscript.

Funding

This research was supported by the Ministry of Higher Education and Scientific Research of Tunisia, under the PRIMA programme (Partnership for Research and Innovation in the Mediterranean Area), funded by the European Union. Project title: “*Innovative sustainable organic sea fennel (Crithmum maritimum L.)-based cropping systems to boost agrobiodiversity, profitability, circularity, and resilience to climate changes in Mediterranean small farms*”.

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