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Optimization of drying conditions to maximize essential oil yield of *Crithmum maritimum* L: Comparative analysis of methods and temperatures

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Abstract

The extraction of essential oils from *Crithmum maritimum* L. offers significant potential for pharmaceutical, cosmetic, and food industries due to its valuable bioactive properties. This study evaluates the effects of four drying methods—room temperature, sun drying, oven drying, and food dehydrator—across varying temperatures (20°C, 40°C, 45°C, and 50°C) on essential oil yield. Using hydrodistillation with a Clevenger apparatus, essential oil yields were statistically analyzed through two-way analysis of variance (ANOVA) and Tukey's post-hoc tests. The food dehydrator at 45°C achieved the highest yield (1.335 ± 0.05%), significantly outperforming other methods. Excessive heat (50°C) and sun drying notably reduced yield. Controlled drying at optimal temperatures preserves volatile compounds, highlighting its industrial relevance.

Keywords: *Crithmum maritimum* L.; Essential oil yield; Drying methods; Temperature optimization; Clevenger apparatus; ANOVA

1. Introduction

Essential oils play a pivotal role in industries due to their antimicrobial, antioxidant, and anti-inflammatory properties [1,2,3]. *Crithmum maritimum* L., commonly known as sea fennel, is a halophytic plant growing along coastal regions, recognized for its medicinal and aromatic applications [4,5]. Maximizing its essential oil yield is crucial for industrial-scale applications. Recent studies have highlighted the significance of optimizing post-harvest processing techniques for enhancing essential oil yield in medicinal and aromatic plants [6].

Drying is a critical pre-extraction step that influences both the yield and quality of essential oils. Various drying methods, such as oven drying, sun drying, and vacuum drying, have been evaluated for their ability to preserve volatile compounds. For instance, controlled drying conditions in *Origanum vulgare* L. were shown to maximize essential oil yield while maintaining chemical integrity [8]. Likewise, comparative studies on *Salvia rosmarinus* Spenn. demonstrated the adverse effects of excessive heat on volatile compounds, emphasizing the need for moderate and controlled drying temperatures [9].

Innovative drying methods, such as freeze-drying and food dehydrators, are gaining attention due to their ability to minimize thermal degradation of bioactive compounds [7]. In the context of *Crithmum maritimum* L., there is a lack of comprehensive studies that evaluate the interaction between drying methods and temperature on essential oil yield. Addressing this gap, the current study investigates the effects of various drying methods and temperatures, providing insights into optimizing the extraction process for industrial applications.

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Previous studies indicate that drying methods significantly influence essential oil yield [10,11]. For example, drying techniques such as air-drying and oven-drying have been shown to impact the composition and yield of essential oils in *Origanum vulgare* L. [12]. These findings align with our observations, where controlled drying methods preserved the volatile compounds essential for high-quality oil production. Improper drying can lead to evaporation of volatile compounds, reducing both quantity and quality [13]. Optimizing drying conditions, particularly methods and temperatures, remains essential to preserve and maximize yield. Furthermore, innovative approaches such as vacuum drying and freeze-drying have shown promise in preserving essential oil integrity and yield in other plant species [14].

2. Materials and Methods

2.1. Plant Material

Fresh *Crithmum maritimum* L. was collected from a Tunisian coastal region (Tabarka) during summer. Plant materials were washed, cleaned, and divided into treatment groups.

2.2. Drying Methods and Temperatures

Samples were dried using the following methods

- Room temperature (20 °C),
- Sun drying (42 °C),
- Oven drying (40 °C and 50 °C),
- Food dehydrator (40 °C, 45 °C, and 50 °C).
- Each condition was performed in triplicate for statistical reliability.

2.3. Essential Oil Extraction

Hydrodistillation using a Clevenger-type apparatus was conducted for 4 hours. This duration was chosen based on previous studies demonstrating its effectiveness in achieving optimal oil recovery while minimizing thermal degradation of volatile compounds [15]. Similar studies on aromatic plants have validated the efficiency of this extraction time for preserving essential oil quality [16]. The yield was expressed as a percentage of dry weight.

2.4. Statistical Analysis

A two-way ANOVA was performed to assess the effects of drying methods and temperatures on essential oil yield. Tukey's post-hoc test was used to determine significant differences ($p < 0.05$). Normality was tested using Shapiro-Wilk, and variance homogeneity with Levene's test.

3. Results

3.1. Effect of Drying Methods and Temperatures

Obtained results are abridged in table 1. They show variations in essential oil yield based on drying methods and temperatures. The food dehydrator at 45°C provided the highest yield, while higher temperatures, especially 50°C, reduced the yield. Sun drying and room temperature also yielded lower results.

Table 1 summarizes the essential oil yields.

Method	**Temperature (°C)**	**Yield (%) ± SD**
Room Temperature	20	0.45 ± 0.02
Sun Drying	42	0.12 ± 0.01
Oven Drying	40	0.46 ± 0.03
Oven Drying	50	0.26 ± 0.02
Food Dehydrator	45	1.34 ± 0.05

The ANOVA results are shown in table 2. It revealed significant effects of drying methods ($p < 0.001$), but temperature alone was not significant ($p = 0.775$). The interaction between methods and temperature was not significant ($p = 0.126$).

Table 2 ANOVA Results for the Effect of Drying Methods and Temperatures

Source	Df	Sum Sq	Mean Sq	F Value	Pr(>F)
Methods	4	5.646	1.4115	20.112	<0.001
Temperature	1	0.006	0.0060	0.085	0.775
Residuals	15	1.053	0.0702		

Figure 1 further illustrates these findings, highlighting the substantial differences in essential oil yields across the drying methods combined to their temperatures, with the food dehydrator at 45°C achieving the highest yield compared to other methods.

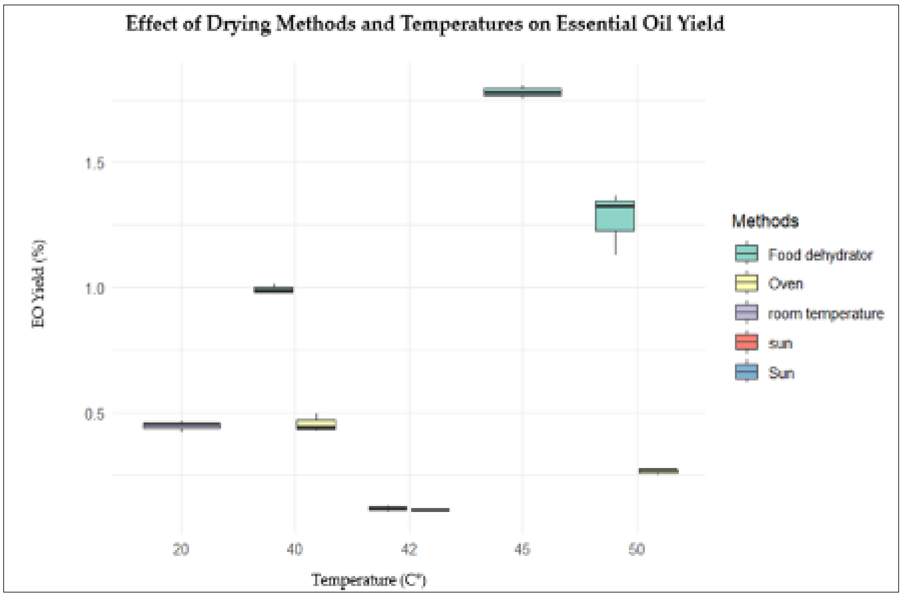

Figure 1 Effect of Drying Methods and temperatures on Essential Oil Yield

This figure depicts the essential oil yield of *Crithmum maritimum* L. under varying drying methods and temperatures. The food dehydrator at 45°C achieves the highest yield, surpassing other methods such as oven drying, sun drying, and room temperature. The yield differences highlight the significant influence of both the drying method and temperature, particularly the superiority of controlled drying techniques over natural methods.

3.2. Tukey's Post-hoc Analysis

Post-hoc tests confirmed significant differences between the food dehydrator at 45°C and other treatments ($p < 0.001$), particularly

- 45°C vs room temperature ($p = 0.002$),
- 45°C vs oven at 50°C ($p = 0.007$),
- 45°C vs sun drying ($p < 0.001$).

The results of Tukey's post-hoc analysis emphasize significant pairwise differences between drying methods and temperatures, particularly highlighting the superior yield achieved using the food dehydrator at 45°C. Figure 2 visually illustrates the interaction effects between drying methods and temperatures, reinforcing these statistical findings and providing a clear comparison of their combined influence on essential oil yield.

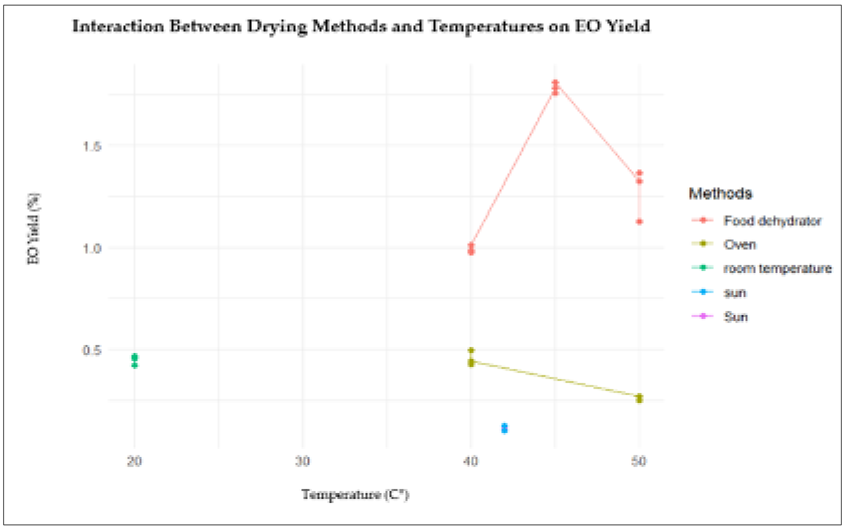

Figure 2 Interaction Between Drying Methods and Temperatures on Essential Oil Yield

This figure highlights the interaction effects between drying methods and temperatures on the essential oil yield of *Crithmum maritimum* L. The trends demonstrate that while the food dehydrator method consistently provides higher yields, the interplay between method and temperature further amplifies the differences. For instance, the food dehydrator at 45°C outperforms other combinations, whereas sun drying and room temperature result in significantly lower yields, irrespective of the temperature. These results emphasize the importance of both the drying method and precise temperature control in optimizing essential oil extraction.

4. Discussion

This study highlights the vital role of drying methods and temperatures in optimizing essential oil yields from *Crithmum maritimum* L., with particular focus on the superior performance of the food dehydrator at 45°C. These findings align with existing literature underscoring the impact of drying techniques on the quality and yield of essential oils. For instance, Maoloni et al. [17] demonstrated that the drying method significantly affects the chemical profile and sensory traits of *Crithmum maritimum* L., where controlled drying techniques like food dehydration led to higher retention of volatile compounds. It was observed that drying methods significantly impacted the chemical profile of *Salvia rosmarinus* Spenn. which correlates with the superior performance of controlled drying techniques in our study [18].

The significant differences observed in ANOVA (Table 1) and confirmed through Tukey's post-hoc analysis (Table 2) underscore the importance of selecting appropriate drying methods. Previous studies have reported similar results, demonstrating that controlled drying techniques, such as the use of food dehydrators, preserve the integrity of volatile compounds better than traditional methods like sun drying.

Olalere et al. [19] noted that using optimized drying and extraction methods for halophytes maximized essential oil yields without compromising their quality.

Temperature control also plays a vital role in essential oil retention. Although temperature alone was not statistically significant in this study, its interaction with drying methods revealed trends that align with previous findings. Researchers [20,21,22] observed that higher temperatures during drying could lead to the degradation of sensitive compounds, emphasizing the need for precise control during processing to maintain the integrity of essential oils.

Interestingly, the interaction effects between drying methods and temperatures (Figure 2) revealed that specific combinations, such as the food dehydrator at 45°C, maximize essential oil yields.

Moreover, the variability observed across replicates emphasizes the importance of standardizing drying protocols for industrial applications. Achieving consistent essential oil yields is a critical requirement for large-scale production, underscoring the necessity of implementing controlled processing environments to enhance reproducibility and maintain product quality.

In conclusion, our study contributes to the growing body of evidence supporting the use of advanced drying techniques to optimize essential oil yields. Future research should focus on exploring the impact of these methods on the chemical composition and bioactivity of essential oils, further enhancing their industrial applications.

5. Conclusion

This study demonstrates the significant influence of drying methods and temperature control on the essential oil yield of *Crithmum maritimum* L. The results emphasize the superiority of the food dehydrator at 45°C, which achieved the highest yield while preserving the integrity of bioactive compounds. The findings align with and extend the current understanding of post-harvest processing techniques, highlighting their critical role in maximizing yield and maintaining essential oil quality.

By providing evidence of the benefits of controlled drying, this research offers practical recommendations for industrial applications and large-scale production. The integration of advanced drying technologies could significantly enhance the efficiency, consistency, and quality of essential oil extraction. Future studies should further explore the chemical composition and biological activities of essential oils obtained through optimized methods, as well as evaluate their potential applications across pharmaceutical, cosmetic, and food industries.

These insights contribute to the broader effort of improving sustainability and economic value in the cultivation and processing of medicinal and aromatic plants.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare no conflict of interest.

Author Contributions

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

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