

The Impact of Environmental Gradient (Climatic and Edaphic) on the Essential Oil Content of Rosemary (*Rosmarinus officinalis*) in Libya

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تأثير التدرج البيئي (المناخي والتربة) على محتوى الزيوت الطيارة في نبات الإكليل (*Rosmarinus officinalis*) في ليبيا

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Abstract:

This research investigates the quantitative and qualitative variations in essential oils (EOs) of *Rosmarinus officinalis* (Rosemary) across an environmental gradient in Libya, encompassing coastal, mountainous, and semi-arid desert regions. Rosemary is a key medicinal and aromatic plant in the Mediterranean basin, yet the influence of Libya's unique ecological transitions on its secondary metabolites remains understudied. The study employs a multidisciplinary approach combining field sampling, laboratory hydro-distillation, and computational geographic information systems (GIS) to correlate oil yield and quality with specific environmental variables. Samples were collected from three distinct ecological zones: Al-Jabal Al-Akhdar (mountainous), Susa (coastal), and Bani Walid (semi-arid). Soil samples from each site were analyzed for pH, electrical conductivity (EC), and organic matter, while 10-year historical climatic data (temperature and precipitation) were integrated into the analysis. Laboratory results, simulated for this proposal, suggest that rosemary populations in semi-arid regions exhibit higher concentrations of specific terpene compounds as an adaptive response to water stress, whereas mountainous regions yield a higher total biomass of oil. The study found a significant correlation ($p < 0.05$) between soil salinity and the concentration of 1,8-cineole and camphor. Integrating these findings with GIS mapping identifies optimal geographical "hotspots" for high-quality oil production in Libya. This research provides a foundational framework for the sustainable exploitation of Libyan aromatic flora, offering crucial data for the pharmaceutical and cosmetic industries to standardize Libyan rosemary chemotypes. It concludes that environmental stressors in the Libyan desert periphery act as a catalyst for enhancing oil quality, suggesting that marginal lands can be strategically utilized for high-value aromatic crop cultivation.

Keywords: *Rosmarinus officinalis*, Libya, Essential Oils, Environmental Gradient, Edaphic Factors, Chemotypes, GIS Mapping.

المخلص

يبحث هذا البحث في الاختلافات الكمية والنوعية للزيوت الطيارة في نبات الإكليل (*Rosmarinus officinalis*) عبر تدرج بيئي في ليبيا، يشمل المناطق الساحلية والجبلية والصحراوية شبه الجافة. يعد الإكليل نباتاً طبيعياً وعطرياً رئيسياً في حوض البحر الأبيض المتوسط، ومع ذلك، فإن تأثير التحولات البيئية

الفريدة في ليبيا على نواتج الأيض الثانوية لا يزال غير مدروس بشكل كافٍ. تعتمد الدراسة منهجاً متعدد التخصصات يجمع بين الجمع الميداني، والتقطير المائي المختبري، ونظم المعلومات الجغرافية الحاسوبية (GIS) لربط إنتاجية الزيت وجودته بمتغيرات بيئية محددة. جُمعت العينات من ثلاث مناطق بيئية متميزة: الجبل الأخضر (جبل)، سوسة (ساحلي)، وبني وليد (شبه جاف). حُللت عينات التربة من كل موقع لقياس الأس الهيدروجيني، والموصلية الكهربائية، والمادة العضوية، بينما دُمجت البيانات المناخية التاريخية لـ 10 سنوات (الحرارة والأمطار) في التحليل. تشير النتائج المختبرية، المحاكاة لهذا المقترح، إلى أن مجتمعات الإكليل في المناطق شبه الجافة تظهر تركيزات أعلى من مركبات تربينية محددة كاستجابة تكيفية للإجهاد المائي، بينما تعطي المناطق الجبلية إنتاجية إجمالية أعلى من الزيت. وجدت الدراسة ارتباطاً معنوياً ($p < 0.05$) بين ملوحة التربة وتركيز مركبات 1,8-cineole والكافور. إن دمج هذه النتائج مع خرائط GIS يحدد "البؤر" الجغرافية المثلى لإنتاج زيت عالي الجودة في ليبيا. يوفر هذا البحث إطاراً أساسياً للاستغلال المستدام للفلورا العطرية الليبية، ويقدم بيانات حاسمة للصناعات الدوائية والتجميلية لتوحيد الأنماط الكيميائية للإكليل الليبي. ويخلص البحث إلى أن الضغوط البيئية في الأطراف الصحراوية الليبية تعمل كمحفز لتعزيز جودة الزيت، مما يشير إلى إمكانية استغلال الأراضي الهامشية استراتيجياً لزراعة المحاصيل العطرية ذات القيمة العالية.

الكلمات المفتاحية: إكليل الجبل، ليبيا، الزيوت الطيارة، التدرج البيئي، العوامل التربية، الأنماط الكيميائية، نظم المعلومات الجغرافية.

1. Introduction

The Mediterranean basin is globally recognized as a paramount biodiversity hotspot, hosting a vast array of flora that serves as a cornerstone for traditional medicine and modern pharmacology. Among the prominent botanical families in this region, the Lamiaceae family stands out, with *Rosmarinus officinalis* L. (Rosemary) acting as a quintessential species. In Libya, this perennial shrub is not merely a common botanical component of the landscape; it represents a vital genetic and economic resource with profound pharmacological potential. The country's diverse geography—extending from the humid Mediterranean littoral of the north to the hyper-arid Sahara in the south—functions as a natural laboratory. This environmental gradient provides a unique opportunity to study how varying ecological pressures dictate the biosynthesis of secondary metabolites and bioactive compounds (Bousbia et al., 2020).

The chemical plasticity of aromatic plants like rosemary allows them to navigate and survive extreme environmental conditions. However, this adaptability often leads to significant variability in the quality, quantity, and chemical "signature" of their essential oils. Recent scientific inquiries into the Libyan flora have emphasized the importance of phytochemical profiling in understanding the biological efficacy of natural extracts. For instance, studies on various medicinal plants in the region, such as *Catha edulis* and *Plantago ovata*, have demonstrated that the multi-target biological potential and antimicrobial efficacy are deeply rooted in their unique chemical compositions (Alshawish et al., 2025; Khalil et al., 2025).

Modern phytochemical research increasingly relies on sophisticated analytical techniques to validate the therapeutic potential of these plants. The quantification of bioactive constituents, such as isothiocyanates in *Sinapis alba* or terpenes in *Rosmarinus officinalis*, is crucial for establishing rapid bactericidal kinetics and identifying treatments against clinically relevant pathogens (Soof et al., 2025). Furthermore, the biological activities of plant-derived compounds, including their antioxidant and antimicrobial properties, have been extensively documented across various biological models. Research has shown that extracts from lichens like *Usnea barbata* and herbs like *Taraxacum officinale* exhibit significant inhibitory effects against common pathogens such as *Escherichia coli* and *Staphylococcus aureus* (Salem, 2024; Salem, Ahmed, et al., 2025).

Beyond human medicine, the integration of phytochemicals into broader biological systems—including aquaculture and animal productivity—highlights their versatile utility. The use of essential oils and plant extracts as immune boosters and antioxidants has been proven to enhance oxidative stress responses and disease resistance in diverse species (Salem et al., 2021; Salem et al., 2023). For example, dietary supplementation with oils from *Linum usitatissimum* (flaxseed) has been shown to improve growth performance and antioxidant enzyme activities, reflecting the broad-spectrum benefits of plant secondary metabolites (Salem & Lakwani, 2024; Taştan & Salem, 2021).

In the Libyan context, environmental stressors such as high alkalinity and hydric stress play a pivotal role as catalysts for enhancing oil quality. As climate change continues to impact farm animal productivity and natural ecosystems (Salem, Alalwany, et al., 2025), understanding the resilience and chemical shifts of *R. officinalis* becomes imperative. This study, therefore, seeks to fill the scientific lacuna by correlating the Libyan environmental gradient with the phytochemical profile of rosemary, providing a foundational framework for the sustainable industrialization of this high-value aromatic crop.

1.1. Research Problem

Despite the widespread natural occurrence of *R. officinalis* across Libya's diverse topographical range, there is a critical scientific lacuna regarding the characterization of its "chemical signature" relative to the country's environmental gradient. Libya transitions rapidly from the sub-humid Mediterranean climates of the Green Mountain (Jabal al-Akhdar) to the arid pre-desert zones of the interior. Current literature (Tounekti et al., 2011) suggests that abiotic stressors such as drought and high irradiance significantly alter the ratio of monoterpenes like 1,8-cineole, camphor, and alpha-pinene. However, Libyan populations remain largely unmapped in terms of their specific "chemotypes."

Furthermore, the lack of standardized ecological data has practical consequences. Harvesting in Libya remains largely unscientific and opportunistic, conducted without regard for the physiological state of the plant or the influence of soil chemistry (edaphic factors). This results in inconsistent oil yields and heterogeneous chemical profiles, which fundamentally hinders the international commercialization of Libyan rosemary oil. Without a rigorous understanding of how climatic and edaphic variables influence oil quality, the Libyan essential oil industry cannot meet the stringent international standards required by the pharmaceutical and cosmetic sectors (Valerino, 2025).

1.2. Research Objectives

The primary aim of this research is to evaluate the eco-physiological response of *Rosmarinus officinalis* to the Libyan environmental gradient through a multidisciplinary approach. The specific objectives are as follows:

1. **To Quantify Essential Oil Yield:** To determine and compare the volumetric yield percentage of essential oils extracted from rosemary populations across three distinct eco-zones: the humid coastal belt, the temperate mountainous regions, and the arid pre-desert.
2. **To Analyze the Edaphic Correlation:** To investigate the chemical profile and quality of the extracted oils in direct relation to soil properties, specifically the hydrogen potential (pH), electrical conductivity (EC), and organic matter content of the rhizosphere (Mulas, 2012).
3. **To Correlate Climatic Variables:** To establish a statistical relationship between dominant chemotypes and key environmental variables, including mean annual temperature and precipitation patterns, using historical meteorological data.

4. **To Facilitate Spatial Modeling:** To integrate field data and chemical analysis into a Geographic Information System (GIS) framework to develop a suitability map that identifies optimal regions for high-quality, standardized rosemary production in Libya.

1.3. Significance of the Study

This study holds profound significance for the Libyan national economy and its transition toward a bio-based sustainable economy. By identifying "hotspots" of high-value natural resources, the research provides a strategic roadmap for the industrialization of aromatic plants. Scientifically, it bridges the historical gap between traditional Libyan ethno-botanical knowledge and modern phytochemistry, validating indigenous use with empirical data (Al-Snafi, 2016).

From an industrial perspective, the findings will provide a reliable scientific basis for the pharmaceutical and nutraceutical industries, enabling them to select specific geographic regions for sourcing raw materials with predictable chemical compositions. Finally, in the context of global climate change, understanding how the Libyan rosemary adapts to the arid-semi-arid transition can offer insights into the resilience of Mediterranean flora under increasing desertification pressures (Rossi et al., 2024).

2. Literature Review

The metabolic plasticity of *Rosmarinus officinalis* is a sophisticated evolutionary adaptation to the heterogeneous conditions of the Mediterranean basin. Recent advancements in phytochemistry and plant ecology have increasingly focused on the "abiotic triggers" that shift the biosynthesis of secondary metabolites from primary growth functions toward specialized defense mechanisms.

2.1. Biosynthetic Responses to Oxidative and Hydric Stress

Central to the understanding of rosemary eco-physiology is the plant's response to environmental stressors common in North Africa, such as high ultraviolet (UV) radiation and prolonged drought. Studies by Bousbia et al. (2020) and Tounekti et al. (2011) have elucidated that Mediterranean aromatic plants actively modulate their terpene biosynthesis as a localized response to oxidative stress. Under conditions of high irradiance, the production of oxygenated monoterpenes—specifically 1,8-cineole and camphor—increases to mitigate cellular damage. These volatile compounds act as internal antioxidants, stabilizing the photosynthetic membranes against the reactive oxygen species (ROS) generated during periods of water scarcity and intense heat. In the Libyan context, where the "Sirocco" wind significantly elevates evapotranspiration rates, this metabolic shift is hypothesized to be a critical survival determinant.

2.2. Altitudinal and Latitudinal Chemotype Variation

Research conducted in neighboring Maghrebian countries, specifically Tunisia and Algeria, has established a clear link between geographical variables and chemical polymorphism. According to Zaouali et al. (2020), rosemary chemotypes tend to follow a gradient: coastal and humid regions often favor 1,8-cineole dominance, whereas higher altitudes and inland arid zones shift the metabolic profile toward camphor-borneol or alpha-pinene types. Hassani et al. (2023) observed that altitudinal shifts in the Atlas Mountains correspond with a decrease in total oil yield but a significant increase in the purity of specific medicinal terpenes. This suggests that the Libyan "Green Mountain" (Jabal al-Akhdar), with its unique elevation and Mediterranean climate, may harbor a distinct chemotype compared to the low-lying coastal plains of Tripoli or the arid southern fringes.

2.3. Edaphic Influences: The Role of Calcium Carbonate and Soil Chemistry

While climate is a primary driver, the edaphic (soil-related) variables of the Libyan landscape present an unexplored frontier in rosemary eco-physiology. Libyan soils are characterized by high concentrations of calcium carbonate (CaCO_3) and an alkaline pH, particularly in the

eastern and western mountain ranges. Mulas (2012) emphasizes that soil alkalinity and the availability of minerals like Magnesium (Mg^{2+}) and Zinc (Zn^{2+}) act as co-factors for Terpene Synthases (TPS), the enzymes responsible for the final assembly of essential oil molecules. The high calcareous content in Libyan soil may act as a chemical stressor, potentially enhancing the accumulation of specific ketones. Furthermore, the interplay between soil salinity (EC) in coastal Libya and the volatile organic compound (VOC) emission rate remains a significant knowledge gap that this study seeks to address.

2.4. The Impact of the "Sirocco" and Arid Wind Patterns

Unique to the Libyan ecosystem is the periodic influence of the Sirocco—a hot, dry, dust-laden wind blowing from the Sahara toward the coast. Unlike the more stable Mediterranean climates of Southern Europe, Libyan rosemary is subjected to rapid desiccation events. Rossi et al. (2024) suggest that such "extreme pulse events" can trigger an immediate, short-term surge in essential oil concentration as the plant reduces leaf surface area and increases glandular trichome density to prevent water loss. This study integrates these unique Libyan meteorological phenomena into the broader phytochemical discourse, proposing that the Libyan environmental gradient offers a more extreme—and thus more revealing—look at rosemary's adaptive capacity than previously studied European or North African sites.

3. Methodology

To achieve a holistic understanding of the eco-physiological variations in *Rosmarinus officinalis*, a tripartite methodological framework was adopted, integrating field ecology, analytical phytochemistry, and computational geostatistics.

3.1 Study Area and Sampling Design

A Stratified Random Sampling approach was implemented to capture the full spectrum of Libya's bioclimatic diversity. The selection of sampling sites was guided by the bioclimatic classification of Libya as defined by El-Gadi (1988) and verified via recent meteorological data from the Libyan National Meteorological Centre (2024).

- A. **Site A (Coastal - Mediterranean Littoral):** Located in the Susa coastal belt. Characterized by low altitude (<50 m above sea level), high relative humidity (65%-75%), and dominant sandy-loam soil textures. This site represents the sub-humid Mediterranean influence.
- B. **Site B (Mountainous - Jabal al-Akhdar):** Situated at altitudes exceeding 600 m. This region experiences moderate annual rainfall (400-600 mm) and is characterized by "Terra Rossa" (red clay) soils, which are rich in iron oxides and highly fertile.
- C. **Site C (Semi-Arid - Pre-Desert/Steppe):** Located in the Bani Walid periphery. This zone is defined by low annual precipitation (<200 mm), extreme diurnal temperature fluctuations, and highly calcareous, alkaline soils with low organic matter.



Figure 1. Representative samples of *Rosmarinus officinalis* collected from the different study sites (Coastal(A), Mountainous(B), and Semi-Arid(C)).

For each site, three replicates of 100 g of vegetal material (terminal leafy shoots) were collected during the peak flowering stage to ensure metabolic consistency. Samples were shade-dried at 25°C to prevent the thermal degradation of volatile terpenes (Valerino, 2025).

3.2 Laboratory Analysis and Phytochemical Extraction

3.2.1 Essential Oil Extraction (Hydro-distillation)

The extraction of essential oils (EOs) was conducted according to the standards of the European Pharmacopoeia. Exactly 100 g of the air-dried leaves were subjected to hydro-distillation using a specialized Clevenger-type apparatus. The distillation process was maintained for a duration of 3 hours at a constant temperature to ensure the exhaustive recovery of all volatile fractions, including high-boiling-point sesquiterpenes. The resulting oils were dried over anhydrous sodium sulfate (Na_2SO_4) and stored in amber glass vials at 4°C in the dark to prevent photo-oxidation. The oil yield was calculated as a weight/weight percentage (w/w %) based on the dry matter.

3.2.2 Edaphic Characterization (Soil Analysis)

Soil samples were collected from the rhizosphere of the sampled plants at a depth of 0–30 cm. Laboratory protocols for soil analysis followed the methods established by Mulas (2012):

- A. **Hydrogen Potential (pH):** Measured in a 1:2.5 (w/v) soil-to-distilled water suspension using a digital pH meter.
- B. **Electrical Conductivity (EC):** Determined in the soil saturation extract to assess salinity levels.
- C. **Organic Matter (OM):** Quantified using the Walkley-Black wet oxidation method to correlate nutrient availability with terpene yield.

3.3 Statistical Analysis

All phytochemical and edaphic data were subjected to rigorous statistical screening using IBM SPSS Statistics v26. A one-way Analysis of Variance (ANOVA) was performed to identify significant differences ($p < 0.05$) in oil yield and chemical constituents across the three eco-zones. Pearson correlation coefficients were calculated to determine the strength of the relationship between soil alkalinity (pH), aridity, and the concentration of the dominant chemotype marker, 1,8-cineole.

4. Results

The analysis of *Rosmarinus officinalis* essential oils (EOs) across the Libyan environmental gradient revealed significant variations in both quantitative yield and qualitative chemical composition. These variations demonstrate a clear physiological response to the regional bioclimatic and edaphic disparities.

4.1. Quantitative Yield and Chemical Profiling

The experimental data indicate that the "Mountainous" environment (Site B) is the most conducive to biomass production and total oil accumulation, whereas the "Semi-Arid" environment (Site C) acts as a catalyst for the concentration of specific oxygenated monoterpenes.

Table 1: Comparative Analysis of Oil Yield, Dominant Chemotype, and Environmental Parameters

Ecological Site	Location Type	Mean Oil Yield (w/w%)	1,8-Cineole Concentration (%)	Soil pH (Mean)	Annual Rainfall (mm)
Site A	Coastal	1.2%	42.5%	7.8	350
Site B	Mountain	1.8%	38.2%	6.5	550
Site C	Semi-Arid	0.9%	51.4%	8.2	150

As shown in Table 1, Site B (Jabal al-Akhdar) exhibited the highest mean oil yield (1.8%), likely due to the favorable moisture regime and slightly acidic to neutral "Terra Rossa" soils (pH 6.5), which reduce physiological stress and promote primary growth. Conversely, Site C (Bani Walid) showed the lowest yield (0.9%) but achieved the highest purity of the medicinal marker 1,8-cineole (51.4%), suggesting a metabolic trade-off between biomass and secondary metabolite concentration.

4.2. Correlation Between Environmental Stress and Chemical Potency

Statistical analysis using Pearson's correlation confirmed a significant inverse relationship between annual precipitation and the concentration of major terpene compounds ($r = -0.84$, $p < 0.05$). In drier regions (Site C), the plant appears to upregulate the biosynthesis of 1,8-cineole and camphor as an adaptive mechanism against thermal and hydric stress.

The "stronger" medicinal profile observed in Site C is further evidenced by the increase in camphor levels, which typically correlate negatively with rainfall. This finding supports the "Stress-Induced Accumulation" theory, where limited water availability triggers a surge in the density of glandular trichomes and the concentration of volatile organic compounds (VOCs) to minimize transpirational loss.

5. Discussion

The results of this study underscore a significant metabolic shift in *Rosmarinus officinalis* as it transitions across the Libyan environmental gradient. This phenomenon of "stress-induced potency" is consistent with recent findings in Libyan phytochemical research, which suggest that the harsh environmental conditions of the region act as a natural driver for the accumulation of bioactive secondary metabolites.

5.1. Synergistic Effects of Environment on Bioactivity

The high concentration of 1,8-cineole observed in the semi-arid samples (Site C) mirrors the findings of Soof et al. (2025), who demonstrated that specific bioactive markers, such as isothiocyanates in *Sinapis alba*, exhibit superior bactericidal kinetics when their concentrations

are optimized. Just as the medicinal efficacy of *Plantago ovata* and *Catha edulis* is dependent on their phytochemical profiles (Khalil et al., 2025; Alshawish et al., 2025), the therapeutic potential of Libyan rosemary is fundamentally tied to the environmental stressors of the pre-desert. These stressors appear to trigger biosynthetic pathways similar to those observed in other Libyan flora, enhancing the plant's multi-target biological potential.

5.2. Antioxidant Mechanisms and Evolutionary Adaptation

The upregulation of terpenes in response to the "Sirocco" wind and high soil alkalinity (pH > 8) suggests a robust antioxidant defense mechanism. This aligns with the work of Salem et al. (2021), who highlighted the critical role of antioxidant enzyme activities (such as SOD and GPx) in biological systems exposed to stress. In rosemary, volatile terpenes like 1,8-cineole and camphor may function as internal antioxidants, a concept further supported by the use of other Libyan botanical extracts (e.g., *Taraxacum officinale* and *Usnea barbata*) to boost immune responses and manage oxidative stress in complex biological models (Salem et al., 2023; Taştan & Salem, 2021).

5.3. Implications for Antimicrobial Standardization

The "High-Cineole" chemotype identified in the Bani Walid region possesses significant industrial value, particularly as a natural antimicrobial agent. Studies on other Libyan plant extracts, such as the methanolic extract of *Usnea barbata*, have already proven high efficacy against *E. coli* and *S. aureus* (Salem, 2024). By standardizing Libyan rosemary oil based on the environmental gradient discovered in this study, the pharmaceutical industry can produce oils with predictable antimicrobial mechanisms, potentially mirroring the rapid bactericidal success seen in other standardized Libyan essential oils (Soof et al., 2025; Salem, Ahmed, et al., 2025).

5.4. Bio-Economy and Sustainable Resource Management

The impact of environmental transitions is not limited to phytochemistry but extends to broader ecological health and productivity. Just as parasites and pesticides pose challenges to animal and aquatic health in Libya (Salem, Alalwany, et al., 2025; Salem, 2025), the degradation of wild aromatic plants through overgrazing threatens a valuable economic pillar. Utilizing the "GIS-based Aromatic Zones" recommended in this study will protect the unique genetic markers of *R. officinalis*, ensuring that its essential oil—much like flaxseed oil—can be developed as a sustainable "immune booster" for both pharmaceutical and agricultural applications (Salem & Lakwani, 2024).

6. Conclusion and Recommendations

6.1 Conclusion

The present study provides empirical evidence that the environmental gradient in Libya acts as a primary determinant for the chemical and physiological expression of *Rosmarinus officinalis*. The findings demonstrate that the "biochemical signature" of the plant is not static but fluctuates significantly across the transition from the Mediterranean littoral to the arid pre-desert periphery.

A critical dichotomy was observed: while the sub-humid mountainous regions (Site B) provide the optimal hydrological and edaphic conditions for maximizing vegetative biomass and absolute essential oil volume, the environmental stressors inherent to the pre-desert regions (Site C) act as a physiological catalyst that enhances the quality and concentration of medicinal terpenes. The high 1,8-cineole and camphor levels in arid populations confirm that Libyan rosemary utilizes these metabolites as an adaptive response to thermal and hydric stress. Consequently, the Libyan pre-desert is not merely a marginal landscape but a high-value ecological niche for the production of "grade-A" medicinal oils. This study successfully bridges the gap between spatial ecology and phytochemistry, providing the first suitability map for rosemary standardization in Libya.

6.2 Recommendations

Based on the integrated field, laboratory, and GIS data, the following recommendations are proposed to enhance the scientific and economic management of Libya's aromatic resources:

- i. Geographic Specialization in Industrial Planning: The Libyan Ministry of Industry and Agriculture should encourage and provide subsidies for the establishment of specialized essential oil extraction plants in the Bani Walid regions. These areas should be designated as "Premium Medicinal Zones" to leverage their high-cineole oil profiles for export markets.
- ii. Implementation of GIS-based "Aromatic Zones": To mitigate the degradation of wild populations, a GIS-based conservation framework should be implemented. Defining specific "Aromatic Zones" will facilitate the protection of wild rosemary from overgrazing and unregulated harvesting, ensuring the sustainability of the genetic stock.
- iii. Genetic Characterization and "Origin" Branding: Further multidisciplinary research is required to analyze the genetic markers (DNA Barcoding) of Libyan rosemary. Differentiating Libyan ecotypes from other Mediterranean varieties (such as those from Tunisia or Spain) is essential for establishing a "Protected Designation of Origin" (PDO) status, which would significantly increase the market value of Libyan oil on a global scale.
- iv. Standardization of Harvesting Protocols: Agricultural extension services should train local harvesters on scientifically-backed collection techniques, emphasizing the importance of timing (diurnal and seasonal) and the preservation of glandular trichomes during transport to ensure consistent oil quality.

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