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# Comparative analysis of essential oils, phenolic compounds, and bioactivity in wild and cultivated *Salvia Rosmarinus*, *Thymbra capitata*, and *Artemisia herba-alba* under semi-arid Tunisian conditions

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## Abstract

The sustainable management of medicinal and aromatic plants is increasingly important due to the threats posed by over-exploitation and climate change. Cultivating medicinal and aromatic plants offers a viable alternative to wild harvesting, ensuring resource conservation while maintaining bioactive compound production. This study characterizes the biochemical properties of wild and cultivated *Salvia Rosmarinus Spenn*., *Thymbra capitata (L.) Cav.*, and *Artemisia herba-alba Asso.* to assess their potential for sustainable valorization. Essential oils were extracted via hydrodistillation and analyzed using gas chromatography–mass spectrometry to determine their chemical composition and yield. Additionally, hydromethanolic extracts were evaluated for total polyphenol and flavonoid content, as well as antioxidant and anti-inflammatory activities. Results showed that cultivation significantly increased essential oil yield in *Salvia Rosmarinus Spenn.* and *Thymbra capitata (L.) Cav.* while preserving their major chemical composition. However, some major compounds of each species were more abundant in wild plants than in cultivated ones. Polyphenol and flavonoid content were also higher in cultivated plants than in wild ones. Antioxidant activity, assessed via the DPPH assay and reducing power, remained similar between wild and cultivated specimens; whereas anti-inflammatory activity was slightly lower in cultivated plants. Overall, these findings suggest that cultivation enhances essential oil yield and phenolic compound content without compromising bioactive properties. This supports the use of cultivated medicinal and aromatic plants as a sustainable alternative to wild harvesting, contributing to biodiversity conservation and the economic valorization of forest resources.

**Keywords** Wild and cultivated plants · Essential oil · Phenolic compounds · Antioxidant activity · Anti-inflammatory activity

## Introduction

Medicinal and aromatic plants (MAPs) play a vital role in traditional medicine, pharmaceutical industries, and functional foods due to their rich bioactive compounds, including essential oils, polyphenols, flavonoids, and alkaloids (Bakkali et al. 2008; Maleš et al. 2022; Roy et al. 2022). These plants are widely recognized for their antioxidant, antimicrobial, and anti-inflammatory properties, making them key ingredients in herbal remedies and modern drug formulations (Parham et al. 2020; Gonfa et al. 2023). Among MAPs, *Salvia Rosmarinus Spenn.*, *Thymbra capitata (L.) Cav*, and *Artemisia herba-alba Asso.* have been extensively studied for their pharmacological benefits and their high content of terpenes, phenolic acids, and flavonoids, which

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contribute to their biological activities (Musolino et al. 2023; Pedreño et al. 2019; Saida et al. 2024).

Traditionally, these plants have been wild-harvested from natural ecosystems, particularly in Mediterranean and semi-arid regions, like Tunisia, where they thrive under diverse environmental conditions (Gamoun and Louhaichi 2024). However, the growing global demand for natural products has led to intensive collection of wild MAPs, raising concerns about their sustainability and long-term availability (Shruti et al. 2024). Overexploitation, habitat destruction, and unsustainable harvesting practices are threatening many MAPs species, necessitating urgent conservation efforts and the development of alternative production strategies (Rosser and Mainka 2002). In addition to human-driven pressures, climate change is emerging as a major threat to MAPs and their natural habitats (Mykhailenko et al. 2024). Rising temperatures, erratic rainfall, droughts, and soil degradation are significantly altering the growth, chemical composition, and distribution of wild medicinal plants (Alum 2024; Hounsou et al. 2024). Studies indicate that extreme climatic conditions trigger stress responses in plants, often leading to changes in essential oil yield and variations in the biosynthesis of key bioactive compounds (Formica et al. 2024; Aqeel et al. 2023).

For instance, drought stress has been shown to increase the concentration of certain secondary metabolites, such as terpenes and phenolics, as part of a plant's defense mechanism (Mahajan et al. 2020; Nicolas-Espinosa et al. 2023). However, prolonged exposure to severe drought or high temperatures can negatively affect biomass production, essential oil yield, and overall plant survival, thereby reducing the availability of medicinal plants in their native ecosystems (Sahu and Giri 2025). These environmental constraints highlight the urgent need to explore sustainable solutions to ensure the continued availability of MAPs without depleting wild populations.

Given the increasing threats posed by climate change and overharvesting, cultivating of MAPs presents a viable alternative to wild collection. It ensures a consistent supply while alleviating pressure on natural ecosystems (Phondani et al. 2016; Marcelino et al. 2023). Cultivation offers several advantages, including: *(1)* optimized growing conditions (e.g., controlled irrigation, nutrient management) that enhance plant biomass and essential oil yield, *(2)* sustainable production that supports biodiversity conservation, and greater standardization of active compounds, which is crucial for pharmaceutical and commercial applications. However, exposure to natural stressors in wild plants may lead to the accumulation of higher concentrations of bioactive secondary metabolites, potentially making them more pharmacologically potent than cultivated varieties. Conversely, cultivated plants often yield greater amounts of essential oil and total phenolic content under controlled conditions; although stress-induced in wild plants can enhanced secondary metabolite production (Laftouhi et al. 2023).

This study aims to characterize and compare the biochemical properties of wild and cultivated *Salvia Rosmarinus Spenn.* (rosemary), *Thymbra capitata (L.) Cav.* (thyme), and *Artemisia herba-alba Asso.* (white wormwood) through analysis of their essential oils and hydro-methanolic extracts. By examining their chemical composition and biological activities, the study seeks to highlight the potential of cultivated MAPs as a sustainable resource that supports biodiversity conservation, promotes economic development, and enhances the valorization of cultivated forest species.

## Materials and methods

### Sampling and collection of the plant material

The plant material (rosemary, thyme, and white wormwood) was collected through repeated visits to various geographical sites as part of a structured sampling program. The characteristics of these sites are detailed in Table 1. Preliminary investigations, guided by oral traditions and local reports on species distribution, helped identify natural habitats across northwestern and north-central Tunisia, with white wormwood also found in the country's southern regions.

**Table 1** Geographical location and characteristics of sampling sites

| Provenance | Site | Altitude (m) | Coordinates (GPS) | Average Temperature (°C/year) | Rainfall (mm/year) | Bioclimatic stage |
|---|---|---|---|---|---|---|
| Neber | Jbal Twila | 415 | 36°19′38″ N 8°45′43″E | 18.5 | 440 | Upper semi-arid |
| Seres | Jbal Maiza | 650 | 36°04′706″N 8°54′970″E | 18.5 | 428.7 | Middle semi-arid |
| El Ksour | Jbal Lahmerna | 830 | 35°54′984″N 9°020′63″E | 19.5 | 384.6 | Lower semi-arid |
| Boulifa-Kef | Experimental station | 521.53 | 36°06′54″'N 8°43′13″E | 17.6 | 356.1 | Upper semi-arid |

National Institute of Meteorology of Tunisia, 2024

Wild rosemary, thyme, and white wormwood were harvested from their natural habitats, while cultivated plants were propagated from cuttings taken from unique wild parents for each species from these sampling sites (Table 1). The cuttings were grown in irrigated experimental plots at the Higher School of Agriculture of Kef– Boulifa, where they were domesticated for two years, with an irrigation frequency of 1 to 3 times per month using water containing less than 1.9 g/L of salt (Fig. 1).

Sampling of the plant species began in early March for rosemary, in July for thyme, and concluded in October for white wormwood, coinciding with the onset of their respective flowering periods. During this stage, 1 to 2 kg of aerial parts—primarily small flower buds—were collected from each species. At each site, five individual plants per species were sampled (i.e., $n = 5$ biological replicates per species and site). No pooling of plant material was performed. Each biological replicate was processed and analyzed independently.

Identification of plant material were carried out by Dr. Ridha El Mokni, botanist in the Laboratory of Botany, Cryptogamy and Plant Biology in the Faculty of Pharmacy of Monastir, where some voucher herbarium specimens' [referred LAM/Sal.rosm., 1103/2021; 1203/2021; 1303/2021; LAM/Thymb.capit., 3707/2021; 3807/2021; 3907/2021; AST/Artem.herb.alb., 49103/2021; 5003/2021; 5103/2021] are preserved in the personal herbarium of Dr. Ridha El Mokni (Herb. R. El Mokni, not listed in Index Herbariorum yet) housed at the Faculty of Pharmacy, University of Monastir, Tunisia.

After harvest, 100 to 200 g of each samples were used to determine their fresh weight (FW). The samples were dried in an oven at 40 °C until their weight stabilized, allowing for the determination of dry weight (DW). A portion of the dried leaf samples was reserved for essential oil extraction, while the remaining samples were ground separately using an electric grinder. The resulting powders were stored under conditions that protected them from light and humidity. For each measurement, technical triplicates were performed to ensure accuracy and reproducibility.

Photo of cultivated rosemary, thyme, and white wormwood at the agricultural experiment station in Kef-Boulifa Tunisia.

## Water content

Water content (WC) was measured in aerial plant parts of each sample from all sites and calculated using the following formula: $((FW\_DW)/FW) * 100$. Each sample per taxon was represented by five plants.

## Essential oil extraction

Essential oils were extracted via hydrodistillation using a Clevenger-type apparatus. Each distillation involved boiling 100 g of leaves powders with 500 mL of distilled water in a flask for 3 h. Each sample per taxon was represented by five plants. The essential oil yield (EOY) was calculated as follows:

$$\%\ \mathrm{EOY} = [(\text{volume of essential oil (ml)})/(\text{quantity of (DW) (g)})]*100$$

### Chemical components of essential oil

Essential oil composition was analyzed using an Agilent Technologies GC-MS (Conquer Scientific, Agilent 6890 gas chromatograph coupled to an Agilent 5973 Mass Selective Detector ) equipped with an HP-5MS column (30 mm × 0.25 mm, 0.25 µm film thickness, 5% Phenyl-Methylpolysiloxane). Helium was used as the carrier gas at a constant flow rate of 1.0 mL/min. The injection volume was 1 µL, and the injection mode was split with a 50:1 ratio. The GC temperature program was set as follows; (1) Initial

**Fig. 1** Cultivated plants at the experimental site of the Higher School of Agriculture of Kef

temperature: 50 °C for 3 min, (2) Temperature increase: 3 °C/min to 240 °C and (3) Injector and transfer line temperatures: 240 °C. Each sample per taxon was represented by three plants.

Compounds were identified by comparing their retention times and Kovats retention indices with reference values from literature and database libraries. The Kovats retention index (RI) was calculated using the formula:

$$\mathrm{RI} = [n + (\mathrm{Log}(\mathrm{RTx}) - \log(\mathrm{RTn}))/(\log(\mathrm{RTN}) - \log(\mathrm{RTn})] \times 100$$

Where:

RI = Kovats retention index, n = Carbon number of the smallest n-alkane, N = Carbon number of the largest n-alkane, RTx = Retention time of the compound, RTn = Retention time of the smallest n-alkane, RTN = Retention time of the largest n-alkane.

## Extraction and quantification of phenolic compounds

Fresh leaves were air-dried at room temperature in the shade, then ground into a fine powder. 0.5 g of powdered leaves was mixed with 5 mL of 70% methanol and stirred at 50 °C for 4 h in a water bath, following the method of Djeridane et al. (Djeridane et al. 2006). The extract was centrifuged at 4500 rpm for 15 min at 25 °C, and the supernatants were collected and stored at 4 °C for further analysis.

## Phenolic extraction yield

Phenolic compounds extract were evaporated in a rotary evaporator at 40 °C (methanol) and 50 °C (water) under 80 mb pressure. The yield of the extracts was expressed in terms of the milligrams of dry methanolic extract per gram of dry plant weight (mg DE/g DPW). Each sample per taxon was represented by five plants. The phenolic extraction Yield (PEY) was calculated as follows:

$$\mathrm{PEY} = (\text{Weight of flask after methanol evaporation} - \text{Weight of empty flask})/\mathrm{DPW}$$

### Total polyphenols

The polyphenol content was determined according to the methods used by Turkmen et al. (Turkmen et al. 2006) with some modifications; 200 µl of extract (0.1 g/mL) was added to 1 ml of Folin–Ciocalteu's reagent. After three minutes, 800 µl of 7.5% sodium carbonate was added, and the absorbance was measured at 765 nm after 30 min of incubation, using UV-Visible spectrophotometer (Ultrospec 7000, GE Healthcare Life Sciences). Gallic acid was used as a standard for the calibration curve (0–1 mg/mL). The contents of polyphenol were expressed as milligrams of gallic acid equivalent per gram of dry matter (mg GAE/g DM). Each sample per taxon was represented by five plants.

### Total flavonoid

The flavonoid content was determined according to the method described by Ci and Indria (Ci and Indira 2016); 1 ml of extract (0.1 g/mL) was mixed with 1 ml of aluminum chloride (AlCl3 2%). After ten minutes of incubation, the absorbance was measured at 430 nm. A standard curve was prepared using quercetin at concentrations ranging from 50 to 500 mg/L The flavonoid content was expressed as milligrams of quercetin equivalent per g of dry matter (mg Qt E/g DM). Each sample per taxon was represented by five plants.

## Antioxidant activity

### Reducing power

The reducing power of the extracts was measured according to the method described by Gülçin et al. (Gülçin et al. 2002). A total of 250 µl of extract (0.1 g/mL) was added to 250 µl of a phosphate buffer solution (0.2 M, pH 6.6) and 250 µl of potassium ferricyanide (1%). After incubating for 20 min at 50 °C, 250 µl of trichloroacetic acid (10%) was added to the mixture. After 5 min of incubation, 500 µl of distilled water and 100 µl of ferric chloride (0.1%) were added. The absorbance was measured at 700 nm after 10 min of incubation. The results are expressed as the equivalent mg of gallic acid per 100 g DM. Each sample per taxon was represented by five plants.

### Antiradical activity of DPPH

The capacity of the extracts to fix free radicals was measured according to the methods of Jakobek et al. (Jakobek et al. 2007). Then, 100 µl of extract (0.1 g/mL) was added to 2.5 ml of DPPH solution (60 µM). After 40 min of incubation, the absorbance was measured at 517 nm. Each sample per taxon was represented by five plants, and Vitamin C (50 µg/mL) was used as a positive standard to validate the procedure during the initial trial. The antiradical power of DPPH is expressed as a percentage:

$$\text{Antiradical power of DPPH.} = [(\mathrm{controlABS} - \mathrm{sampleABS})/\mathrm{controlABS}] \times 100$$

### Anti-inflammatory activity

The anti-inflammatory activity of plant extracts was evaluated by measuring the inhibition of 5-lipoxygenase, following the method described by Baylac and Racine (Baylac and Racine 2003) with some modifications. A total of 200 µL of extract (0.1 g/mL) was mixed with 1.8 mL of methanol, followed by the addition of 1 mL of borate buffer (0.1 M, pH 6.3) and linoleic acid (100 µM). The reaction was initiated by adding 10 µL of 5-lipoxygenase diluted in phosphate buffer. After 10 min of incubation, the reaction mixture was analyzed using UV spectrometry at 234 nm. Each sample per taxon was represented by five plants, and quercetin (0.1 mg/mL) was used as a positive standard to validate the procedure during the initial trial. Inhibition was indicated by a decrease in the reaction rate, and the percentage of inhibition was calculated using the following formula:

$$I(\%). = [\text{Ablank} - \text{Asample})/\text{Ablank}] \times 100$$

### Statistical analysis

All results are presented as means ± standard deviation (SD) based on triplicate measurements. One-way analysis of variance (ANOVA) was conducted separately for each species (rosemary, thyme, and white wormwood) to compare wild and cultivated samples across different collection sites. Statistical analyses were performed using IBM SPSS Statistics (version 20). Post hoc comparisons among sites were carried out using Duncan's multiple range tests where appropriate. Differences between wild and cultivated samples within the same site were assessed using Student's t-test. Statistically significant differences are denoted by asterisks: $*p<0.05$ and $**p<0.01$. In tables and histograms, site-specific differences are indicated by superscript letters (a, b, c).

## Results

In our analysis, we compared the same plant species across three sites and between the cultivated and wild types independently for each plant species.

### Variation in water content among plant samples

Water is an essential element for plant growth, and its retention depends on edaphic and climatic conditions. The WC

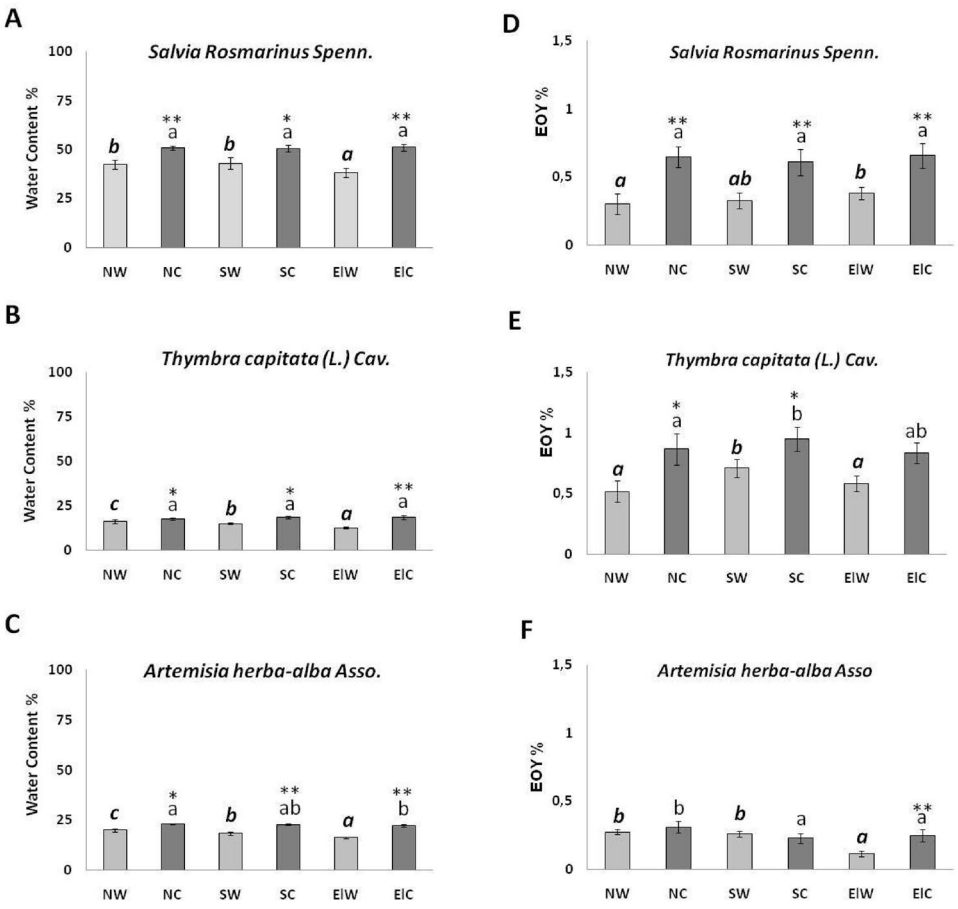


**Fig. 2** histograms of water and essential oil content in leaves of different plants

in leaves can vary according to these factors. Figure 2A, B, and C illustrates the differences in WC between wild and cultivated plants. The histograms indicate a significant difference ($P<0.05$) in leaf WC between the two groups. A particularly notable difference was observed in rosemary in El Ksour (Fig. 2A), where wild plants had a WC of 38.19±2.41%, compared to 51.12±1.80% in cultivated plants. Thyme and white wormwood also showed significant differences between wild and cultivated plants (Fig. 2B and C). Additionally, significant differences (a, b, and c) were observed in wild plants across different sampling sites (Fig. 2A, B, and C). These variations in leaf WC reflect the environmental variability affecting these species, particularly in 2024—a year marked by high temperatures and low rainfall.

## Essential oil yield in study samples

The essential oil yield (EOY) of plants is a valuable indicator of the influence of edaphic and climatic factors on the growth, adaptation, and development of wild and cultivated medicinal herbs. Figure 2D, E, and F illustrate the differences in essential oil content between wild and cultivated plants. The histograms (Fig. 2D) indicate a significant difference ($p<0.01$) in EOY between wild and cultivated rosemary across all provenances. The highest EOY was observed in cultivated rosemary from El Ksour (0.66% ± 0.09%), while the lowest was recorded in wild rosemary from Neber (0.30% ± 0.07%). Similarly, thyme showed a significant difference ($p<0.01$) in EOY between wild and cultivated plants (Fig. 2E). Cultivated thyme exhibited a higher EOY, with the highest yield recorded in samples from Seres (0.95% ± 0.09%), whereas the lowest was detected in wild thyme from Neber (0.51%±0.08%). White wormwood also showed a significant increase in EOY in cultivated plants compared to wild ones from the El Ksour provenance (0.25% ± 0.02% vs. 0.12% ± 0.05%) (Fig. 2F). However, no significant differences in EOY were observed between wild and cultivated white wormwood from the Neber and Seres provenances, likely due to the species' naturally low essential oil production.

These findings underscore the crucial role of water availability (irrigation) and edaphic and climatic conditions in essential oil production in plants.

Variation in water content and essential oil yield of the studied plants across all sampling sites. (A, B, C) Histograms showing water content in wild and cultivated rosemary, thyme, and white wormwood, respectively, collected from different regions. (D, E, F) Histograms depicting essential oil yield in wild and cultivated plants from all sampling sites. Sample size ($n=5$) refers to five individual plants (biological replicates) and each measurement was performed in technical triplicates. Significant differences in water and essential oil content in the leaves of wild plants—NW (Neber wild plant), SW (Seres wild plant), and ElW (El Ksour wild plant)—are indicated by bold letters (***a***, ***b***, ***c***). Differences among the cultivated plants—NC (Neber cultivated plant), SC (Seres cultivated plant), and ElC (El Ksour cultivated plant)—are indicated by regular (non-bold) letters (a, b, c) across the sampling sites. Comparisons between wild and cultivated species are reported using the following significance levels: (*) $p\leq0.05$, (**) $p\leq0.01$, and (ns) for non-significant differences. Means labeled with different letters are considered statistically different at the 5% probability level.

## Chemical composition of essential oils

The chemical compositions of the essential oils from wild and cultivated rosemary plants are presented in Tables 2, 3 and 4. A comparison of these compounds reveals a significant difference ($P<0.05$) between wild and cultivated plants. The major chemical constituents of rosemary essential oil are eucalyptol, α-pinene, camphor, camphene, and borneol. Wild rosemary shows a higher concentration of eucalyptol in El Ksour (63.32% ± 1.41%), Neber (59.24% ± 1.20%), and Seres (61.46% ± 1.15%) compared to cultivated rosemary, which contains 41.70% ± 1.33%, 40.66%± 1.35%, and 44.40% ± 0.99% in these respective locations. In contrast, α-pinene is more abundant in cultivated rosemary, with levels of 15.52% ± 0.80%, in Seres, 20.89% ± 0.32%, in Neber, and 18.26% ± 0.50%, in El Ksour, compared to 12.07% ± 0.44%, 16.10% ± 0.60%, and 11.68% ± 0.91% in wild rosemary from the same regions. Similarly, camphene is found in higher concentrations in cultivated rosemary (9.99% ± 0.90 −12.85% ± 1.04%) than in wild rosemary (5.15% ± 0.57–6.86% ± 0.50%). However, there is no significant difference in camphor and borneol levels between cultivated and wild rosemary (Table 2). Other chemical compounds are present in smaller quantities, with some being absent in either wild or cultivated plants, as well as varying across sampling sites (Table 2). Thyme and white wormwood exhibit distinct chemical compositions in their essential oils. In thyme essential oil (Table 3), major compounds include thymol, p-cymene, and γ-terpinene, along with other substances such as α-pinene, camphene, camphor, borneol, caryophyllene, and caryophyllene oxide. However, there is no significant difference in the majority of these compounds between cultivated and wild thyme or across sampling sites. Significant differences ($P<0.05$) are observed for p-cymene and γ-terpinene: wild thyme essential oil contains a higher concentration of p-cymene in Neber (5.43% ± 0.71%) compared to the cultivated type (3.26% ± 0.65% in Neber), whereas γ-terpinene is found in

**Table 2** Chemical composition of the essential oils of cultivated and spontaneous Rosemary

| Compounds | RI | Salvia Rosmarinus Spen (%) | | | | | |
|---|---|---|---|---|---|---|---|
| | | NW | *N* C | SW | S C | ElW | ElC |
| Tricyclene | 904 | 0.16±0.04 | 0.07±0.01 | 0.19±0.03 | 0.11±0.06 | 0.17±0.08 | 0.09±0.01 |
| α-Pinene | 916 | 16.1±0.60 $^{b}$ | 20.89±0.32 $^{b\,*}$ | 12.07±0.44 $^{a}$ | 15.18±0.80 $^{a}$ | 11.68±0.91$^{a}$ | 18.31±0.50 $^{a.b\,*}$ |
| Camphene | 933 | 5.15±0.57$^{a}$ | 11.67±0.70 $^{a\,*}$ | 6.86±0.50$^{a}$ | 9.99±0.90$^{a\,*}$ | 5.61±0.55$^{a}$ | 12.85±1.04 $^{a.b\,*}$ |
| β-Pinene | 963 | 0.4±0.09 $^{a}$ | 6.07±0.60 $^{a\,**}$ | 0.65±0.20 $^{a}$ | 9.22±1.20 $^{b\,**}$ | 0.54±0.15$^{a}$ | 7.56±0.85 $^{a.b**}$ |
| β-Myrcene | 988 | 1.44±0.21 | 0.78±0.10 | | | | |
| Eucalyptol | 1014 | 59.24±1.20 $^{a\,*}$ | 40.66±1.35 $^{a}$ | 61.46±1.15 $^{a.b\,*}$ | 44.42±0.99$^{b}$ | 63.32±1.41$^{b\,*}$ | 41.7±1.33 $^{a.b}$ |
| p-Cymene | 1024 | | | | | | |
| γ-Terpinene | 1062 | | | | | 0.23±0.04 | 2.47±0.28 |
| Thujone | 1067 | | | | | | |
| p-Chrysanthenone | 1113 | | | | | | |
| Camphor | 1135 | 8.16±0.97 $^{a}$ | 12.93±0.61$^{a.b\,*}$ | 11.37±1.05 $^{b}$ | 13.9±0.72 $^{b\,*}$ | 9±0.33 $^{a.b}$ | 11.01±0.91 $^{a\,*}$ |
| Borneol | 1160 | 2.38±0.30 $^{b}$ | 2.49±0.25 $^{b}$ | 1.27±0.60 $^{a}$ | 2.97±0.50 $^{b\,*}$ | 2.13±0.44 $^{b}$ | 1.41±0.52 $^{a}$ |
| Verbenone | 1223 | 0.09±0.02 | 0.23±0.04 | 0.16±0.03 | 0.43±0.10 | 0.12±0.02 | 0.49±0.12 |
| Geraniol | 1265 | 0.41±0.08 | 0.9±0.10 | | | | |
| Bornyl acetate | 1280 | 0.66±0.09 | 1.28±0.15 | 0.84±0.11 | 1.49±0.21 | 1.1±0.09 | 1.89±0.14 |
| Thymol | 1301 | | | | | | |
| Carvacrol | 1316 | 2.78±0.85 $^{b\,*}$ | 0.55±0.05 $^{a}$ | 1.87±0.65 $^{a\,*}$ | 0.47±0.06 $^{a}$ | 2.79±0.85$^{b\,*}$ | 0.58±0.12 $^{a}$ |
| Caryophyllene | 1419 | 0.63±0.11 | 0.09±0.01 | 0.97±0.09 | 0.06±0.01 | 0.81±0.10 | 0.09±0.02 |
| Humulene | 1456 | 0.61±0.10 | 0.09±0.02 | 0.29±0.08 | 0.09±0.01 | 0.43±0.09 | 0.02±0.00 |
| Caryophyllene oxide | 1590 | 0.24±0.04 | 0.02±0.00 | 0.27±0.05 | 0.09±0.02 | 0.31±0.06 | 0.05±0.01 |
| Total | | 98.47±0.13 | 98.73±0.11 | 98.27±0.13 | 98.43±0.11 | 98.24±0.13 | 98.52±0.11 |

**Table 3** Chemical composition of the essential oils of cultivated and spontaneous thyme

| Compounds | RI | Thymbra capitata (L.) Cav. (%) | | | | | |
|---|---|---|---|---|---|---|---|
| | | NW | NC | SW | SC | ElW | ElC |
| Tricyclene | 904 | | | | | | |
| α-Pinene | 916 | 1.47±0.13 | 0.93±0.3 | 1.21±0.18 | 0.54±0.02 | 1.47±0.15 | 0.51±0.09 |
| Camphene | 933 | 0.5±0.08 | 0.23±0.05 | 0.27±0.02 | 0.12±0.02 | 0.47±0.09 | 0.21±0.05 |
| β-Pinene | 963 | | | | | | |
| β-Myrcene | 988 | | | | | | |
| Eucalyptol | 1014 | | | | | | |
| p-Cymene | 1024 | 5.43±0.71 $^{b\,*}$ | 3.26±0.65 $^{b}$ | 4.85±0.45 $^{a.b\,*}$ | 2.21±0.52 $^{a}$ | 3.61±0.7 $^{a\,*}$ | 2.57±0.35$^{a.b}$ |
| γ-Terpinene | 1062 | 3.53±0.32 $^{b}$ | 8.89±0.61 $^{b\,*}$ | 2.08±0.55 $^{a.b}$ | 6.07±0.30 $^{a\,*}$ | 1.71±0.11 $^{a}$ | 6.63±0.52 $^{a\,*}$ |
| Thujone | 1067 | | | | | | |
| p-Chrysanthenone | 1113 | | | | | | |
| Camphor | 1135 | 0.58±0.04 | 0.14±0.04 | 0.21±0.07 | 0.04±0.00 | 0.23±0.02 | 0.04±0.00 |
| Borneol | 1160 | 0.07±0.01 | 0.83±0.21 | 0.13±0.01 | 0.69±0.11 | 0.41±0.01 | 0.71±0.12 |
| Verbenone | 1223 | | | | | | |
| Geraniol | 1265 | | | | | | |
| Bornyl acetate | 1280 | | | | | | |
| Thymol | 1301 | 84.52±1.41$^{a\,*}$ | 81.35±0.97 $^{a}$ | 86.99±1.01 $^{a\,*}$ | 84.85±1.67 $^{a}$ | 87.8±0.96 $^{a}$ | 84.59±1.7 $^{a}$ |
| Carvacrol | 1316 | | | | | | |
| Caryophyllene | 1419 | 2.19±0.45 | 2.63±0.53 | 2.74±0.37 | 3.72±0.55 | 1.92±0.15 | 3.3±0.35 |
| Humulene | 1456 | | | | | | |
| Caryophyllene oxide | 1590 | 0.62±0.03 | 0.27±0.08 | 0.46±0.06 | 0.12±0.04 | 0.4±0.02 | 0.25±0.01 |
| Total | | 98.91±0.1 | 98.54±0.1 | 98.94±0.1 | 98.36±0.1 | 98.02±0.1 | 98.81±0.1 |

higher concentrations in cultivated thyme (8.89% ± 0.61% in Neber) and in lower concentrations in wild thyme (1.71% ± 0.11% in El Ksour). This highlights significant differences ($P<0.05$) in these compounds across sampling sites (Table 3). White wormwood essential oil exhibits a notably variable chemical profile between cultivated and wild plants across all sampling sites (Table 4). The major constituents include camphor, eucalyptol, camphene, and thujone, with their concentrations differing significantly depending on the plant type and location. Camphor was most abundant in wild

**Table 4** Chemical composition of the essential oils of cultivated and spontaneous white Wormwood

| Compounds | RI | Artemisia herba-alba Asso. (%) | | | | | |
|---|---|---|---|---|---|---|---|
| | | NW | NC | SW | SC | ElW | ElC |
| Tricyclene | 904 | 0.47±0.10 | 0.34±0.09 | 0.44±0.11 | 0.30±0.07 | 0.49±0.14 | 0.65±0.17 |
| α-Pinene | 916 | 0.73±0.12 | 0.51±0.10 | 0.89±0.12 | 0.26±0.08 | 0.98±0.12 | 0.57±0.10 |
| Camphene | 933 | **12.80±0.98$^{a*}$** | **10.37±1.06$^{a}$** | **11.64±0.96$^{a*}$** | **10.15±1.01$^{a}$** | **12.37±1.16$^{a}$** | **10.51±1.11$^{a}$** |
| β-Pinene | 963 | | | | | | |
| β-Myrcene | 988 | | | | | | |
| Eucalyptol | 1014 | **19.48±0.47$^{b}$** | **21.24±1.07$^{b*}$** | **16.24±0.98$^{a}$** | **19.42±1.01$^{a.b*}$** | **15.77±0.75$^{a}$** | **17.67±0.86$^{a*}$** |
| p-Cymene | 1024 | | | | | | |
| γ-Terpinene | 1062 | | | | | | |
| Thujone | 1067 | **7.11±0.81$^{a}$** | **9.75±0.66$^{a*}$** | **11.30±0.70$^{b}$** | **12.78±0.53$^{b*}$** | **9.40±0.44$^{a.b}$** | **11.17±0.65$^{a.b*}$** |
| p-Chrysanthenone | 1113 | 0.41±0.04 | 0.98±0.14 | 0.53±0.09 | 0.78±0.12 | 0.28±0.03 | 0.80±0.10 |
| Camphor | 1135 | **56.39±1.16$^{a*}$** | **52.03±0.96$^{a}$** | **56.38±1.01$^{a*}$** | **50.96±1.85$^{a}$** | **58.47±2.02$^{a}$** | **52.90±1.96$^{a}$** |
| Borneol | 1160 | 0.23±0.01 | 2.46±0.41 | 0.28±0.01 | 2.73±0.61 | 0.31±0.11 | 3.26±0.81 |
| Verbenone | 1223 | | | | | | |
| Geraniol | 1265 | 0.09±0.01 | 0.12±0.01 | 0.24±0.08 | 0.35±0.07 | 0.19±0.01 | 0.35±0.05 |
| Bornyl acetate | 1280 | | | | | | |
| Thymol | 1301 | | | | | | |
| Carvacrol | 1316 | | | | | | |
| Caryophyllene | 1419 | 0.48±0.04 | 0.23±0.02 | 0.89±0.10 | 0.45±0.04 | 0.67±0.06 | 0.34±0.05 |
| Humulene | 1456 | | | | | | |
| Caryophyllene oxide | 1590 | 0.03±0.00 | 0.14±0.02 | 0.08±0.01 | 0.28±0.05 | 0.04±0.01 | 0.17±0.03 |
| Total | | 98.22±0.08 | 98.17±0.08 | 98.91±0.08 | 98.46±0.08 | 98.97±0.08 | 98.38±0.08 |

plants from El Ksour (58.47% ± 2.02%) and least abundant in cultivated plants from Neber (50.96% ± 1.85%). Eucalyptol reached its highest concentration in cultivated plants from Neber (21.24% ± 1.07%) and its lowest in wild plants from El Ksour (15.77% ± 0.75%). Camphene was most prominent in wild plants from Neber (12.80% ± 1.07%) and least in wild plants from Seres (10.15% ± 1.01%). Thujone showed the highest level in cultivated plants from Seres (12.78% ± 0.53%) and the lowest in wild plants from El Ksour (7.11% ± 0.81%). In addition to these major components, smaller amounts of compounds such as tricyclene, α-pinene, caryophyllene, and p-chrysanthenone were also detected. Overall, significant differences in the concentration of most compounds were observed between the essential oils of wild and cultivated white wormwood (Table 4).

Across all essential oil profiles of these species, certain molecules are present in high concentrations in each plant, while others appear in smaller amounts or only as trace compounds. However, most compounds are found in varying concentrations across all essential oil samples, with significant differences observed between sampling sites. This suggests that species characteristics, bioclimatic stages, and environmental conditions play a key role in shaping the chemical composition of essential oils in the studied plants.

Tables 2 and 3, and 4 present the differences in essential oil (EO) composition of rosemary, thyme, and white wormwood between cultivated and wild plants across all sampling sites. The Sample size ($n=3$) refers to three individual plants. Each measurement was performed in technical triplicates. Superscript letters (a, b, c) denote statistically significant differences in the concentration of chemical compounds among wild plants [NW (Neber wild), SW (Seres wild), ElW (El Ksour wild)] or among cultivated plants [NC (Neber cultivated), SC (Seres cultivated), ElC (El Ksour cultivated)] across the sampling sites. Differences in EO composition between wild and cultivated specimens are indicated as follows: (*) $p \leq 0.05$, (**) $p \leq 0.01$. Means sharing different letters are significantly different at the 5% probability level. RI: Retention Indices.

## Phenolic compound content

### Extraction yield of phenolic compounds

Statistical analysis of this study revealed a significant difference in phenolic compound content between wild and cultivated plants (Fig. 3).

The phenolic extraction yield (PEY) varied significantly ($P<0.05$ and $P<0.01$) between wild and cultivated rosemary across all sampling regions (Fig. 3A). In El Ksour, PEY values were 154.21±1.87 mg DE/g DPW (wild) and 169.21±15.61 mg DE/g DPW (cultivated). In Neber, wild plants had a PEY of 156.87±6.76 mg DE/g DPW, while cultivated plants showed a higher yield of 179.86±10.19 mg DE/g DPW. Similarly, in Seres, PEY values were 162.36±2.9 mg DE/g DPW for wild plants and 177.65±8.61 mg DE/g DPW for cultivated plants. However, no significant differences in PEY were observed

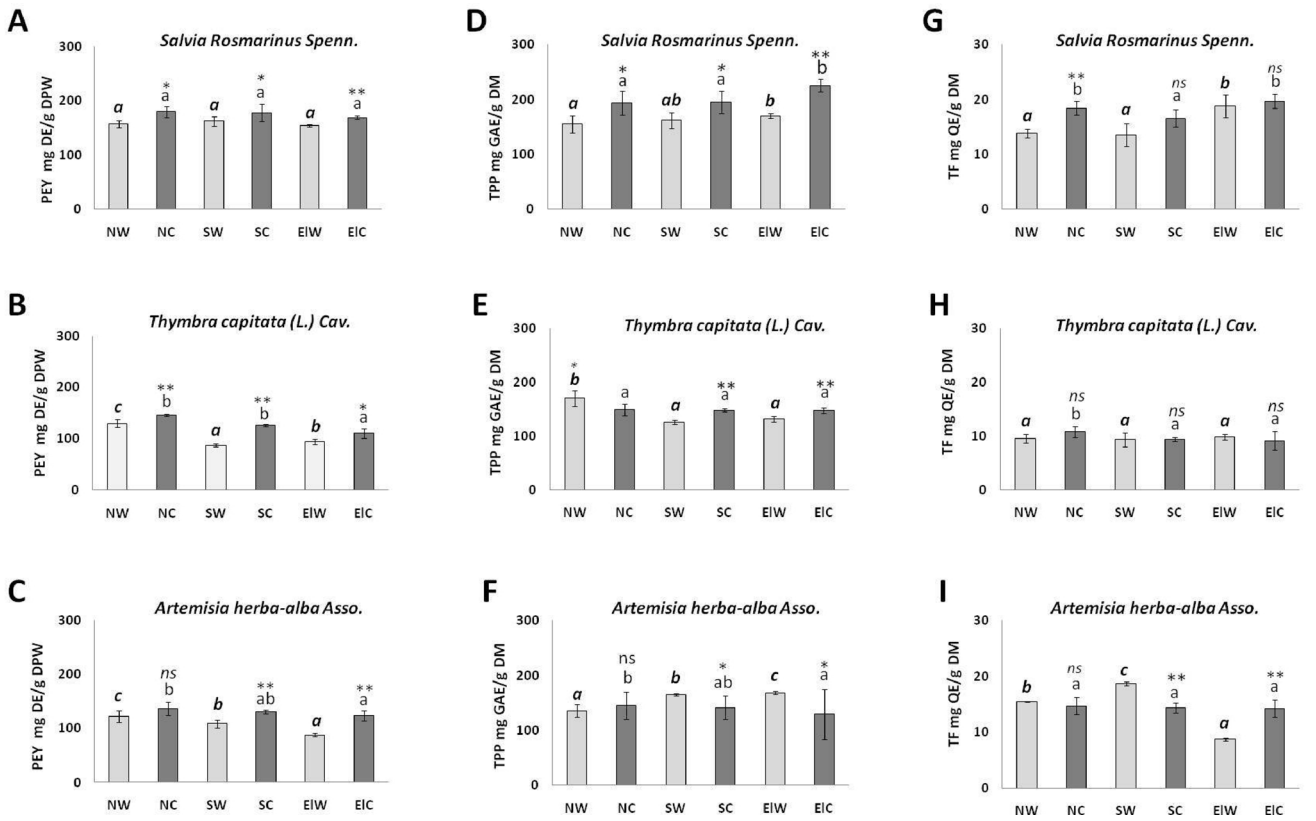


**Fig. 3** Histograms of Extraction Yield of Phenolic Compounds, Total Polyphenols, and Flavonoid Content in Leaf Extracts of Different Plants

between wild and cultivated rosemary across all sampling sites (Fig. 3A).

Likewise, significant differences ($P<0.05$ and $P<0.01$) in PEY were observed between wild and cultivated thyme across all provenances (Fig. 3B). PEY values were lower in wild thyme compared to cultivated thyme, which exhibited the highest PEY in Neber (145.57 ± 2.7 mg DE/g DPW), followed by Seres (125.49 ± 2 mg DE/g DPW) and El Ksour (110.30 ± 9.5 mg DE/g DPW).

For white wormwood, PEY significantly increased ($P<0.01$) in cultivated plants from Seres and El Ksour (Fig. 3C). Wild white wormwood had lower PEY values in El Ksour (88.11 ± 2.65 mg DE/g DPW) and Neber (108.75 ± 7 mg DE/g DPW) compared to cultivated plants, which showed higher yields of 123.44 ± 9.53 mg DE/g DPW in El Ksour and 131.06 ± 3.25 mg DE/g DPW in Seres. However, in Neber, which shares the same bioclimate as the cultivation site, no significant difference in PEY was observed.

This figure illustrates the variation in extraction yield, total polyphenol content, and flavonoid content in the studied plants across all sampling sites. (A, B, C) Histograms represent the extraction yield of phenolic compounds in wild and cultivated rosemary, thyme, and white wormwood, respectively, collected from different regions. (D, E, F) Histograms depict the total polyphenol content in wild and cultivated plants from all sampling sites. (G, H, I) Histograms show the total flavonoid content in wild and cultivated plants across all sampling regions. Sample size ($n=5$) refers to five individual plants and each measurement was performed in technical triplicates. Significant differences in extraction yield, total polyphenol content, and flavonoid content among the leaves of wild plants—NW (Neber wild plant), SW (Seres wild plant), and ElW (El Ksour wild plant)—are indicated by bold letters (***a***, ***b***, ***c***). Differences among the cultivated plants—NC (Neber cultivated plant), SC (Seres cultivated plant), and ElC (El Ksour cultivated plant)—are indicated by regular (non-bold) letters (a, b, c) across the sampling sites. Comparisons between wild and cultivated species are reported using the following significance levels: (*) $p\leq0.05$, (**) $p\leq0.01$, and (ns) for non-significant differences. Means labeled with different letters are considered statistically different at the 5% probability level.

## Total polyphenol content

Statistical analysis revealed a significant difference ($P<0.05$) in total polyphenol (TPP) content between cultivated and wild plants across all sampling sites (Fig. 3D, E, and F). TPP content was significantly higher in cultivated rosemary compared to wild plants (Fig. 3D). Wild rosemary contained

154.74 ± 15.28 mg GAE/g DM in Neber, 161.63 ± 14.77 mg GAE/g DM in Seres, and 169.92 ± 4.43 mg GAE/g DM in El Ksour. In contrast, cultivated rosemary exhibited higher TPP concentrations of 193.14 ± 22.18 mg GAE/g DM, 194.95 ± 21.18 mg GAE/g DM, and 225.23 ± 11.71 mg GAE/g DM at the same respective sites. A significant difference ($P < 0.01$) in TPP content was also observed between wild and cultivated thyme (Fig. 3E). Wild thyme contained 131.14 ± 5.04 mg GAE/g DM in El Ksour and 126.02 ± 3.35 mg GAE/g DM in Seres. Meanwhile, cultivated thyme exhibited higher TPP concentrations of 147.57 ± 4.81 mg GAE/g DM and 148.19 ± 3.53 mg GAE/g DM at the corresponding sites. However, in Neber, no significant difference in TPP content was observed between wild and cultivated thyme. For white wormwood, TPP content varied significantly ($P < 0.05$) between wild and cultivated plants across provenances (Fig. 3F). Wild white wormwood contained 168.42 ± 1.08 mg GAE/g DM in El Ksour and 165.01 ± 0.85 mg GAE/g DM in Seres. In contrast, cultivated plants had TPP values of 129.25 ± 14.99 mg GAE/g DM in El Ksour and 141.48 ± 7.10 mg GAE/g DM in Seres. However, in Neber, no significant difference in TPP content was found between wild and cultivated white wormwood.

### Total flavonoid content

Flavonoids are pigments widely distributed in the plant kingdom and represent an important class of polyphenolic compounds. The flavonoid content was determined using a standard quercetin calibration curve. Our results showed that the total flavonoid (TF) content in cultivated plants was significantly higher ($P < 0.05$) than in wild plants in the Neber and Seres regions. In rosemary, TF content increased from 13.75 ± 0.78 mg EQ/g DM to 18.40 ± 1.30 mg EQ/g DM in Neber and from 13.55 ± 2.06 mg EQ/g DM to 16.55 ± 1.56 mg EQ/g DM in Seres. However, in the El Ksour provenance, no significant difference in TF content was observed between wild and cultivated rosemary plants (Fig. 3G).

Analysis of TF content in thyme revealed significant differences ($P < 0.05$) between wild and cultivated plants only at the Neber sampling site, where cultivated thyme had a higher TF concentration (10.78 ± 1.05 mg EQ/g DM) compared to wild thyme (9.51 ± 0.84 mg EQ/g DM) (Fig. 3H). Additionally, no significant differences in TF content were observed among wild thyme across all sampling sites. For white wormwood, TF content varied significantly ($P < 0.05$) between wild and cultivated plants across regions (Fig. 3I). In Seres, wild white wormwood exhibited a higher TF content (18.71 ± 0.35 mg EQ/g DM) compared to cultivated plants (14.37 ± 0.87 mg EQ/g DM). Conversely, in El Ksour, cultivated plants had a higher TF concentration (14.28 ± 1.49 mg EQ/g DM) compared to wild plants (8.75 ± 0.28 mg EQ/g DM).

## Antioxidant activity

### Antiradical activities

The antiradical activity of plant extracts was evaluated by measuring their ability to neutralize the free radical DPPH. In the presence of an antioxidant, DPPH is reduced to DPPH-H. Our statistical analysis revealed that the DPPH-based antiradical activity was high in all plant extracts. However, no significant differences were observed between wild and cultivated plants across all sampling sites. Additionally, the percentage of antioxidant activity in rosemary, thyme, and white wormwood remained relatively stable in both cultivated and wild plants (Fig. 4A, B, and C). The antioxidant activity was significantly higher in thyme leaves compared to rosemary and white wormwood. The highest level was recorded in wild thyme from El Ksour (92.59% ± 1.97%), while the lowest was observed in wild white wormwood from the same site (53.37% ± 1.39%).

*Reducing Power*.

The reducing power of rosemary and thyme leaf extracts showed no significant differences between cultivated and wild plants across all sampling sites (Fig. 4D and E). However, in white wormwood, a significant difference ($P < 0.05$) was observed. In Neber and El Ksour, the highest reducing power was recorded in wild white wormwood (103.71 ± 7.10 mg/100 g DM and 104.18 ± 6.77 mg/100 g DM, respectively), whereas the lowest was observed in cultivated white wormwood (95.53 ± 2.98 mg/100 g DM). Conversely, in Seres, cultivated white wormwood exhibited higher reducing power, while wild white wormwood had lower values (Fig. 4F).

### Anti-inflammatory activity

The anti-inflammatory activity was evaluated in vitro using the 5-lipoxygenase inhibition method. Statistical analysis revealed a significant difference ($p < 0.05$) in anti-inflammatory potential between wild and cultivated plants in some regions (Fig. 5). The highest activity was recorded in wild rosemary from El Ksour (79.34% ± 2.95%) compared to cultivated plants (56.70% ± 8.34%). Similar trends were observed for Neber, but not for Seres, indicating no significant difference between cultivated and wild plants in that case. However, the anti-inflammatory activity of rosemary extract, whether from cultivated or wild sources, showed a significant difference (a and b) across all regions (Fig. 5A). In contrast, thyme extract exhibited a significant difference ($p < 0.05$) only in El Ksour, where the cultivated plant demonstrated a higher anti-inflammatory potential compared

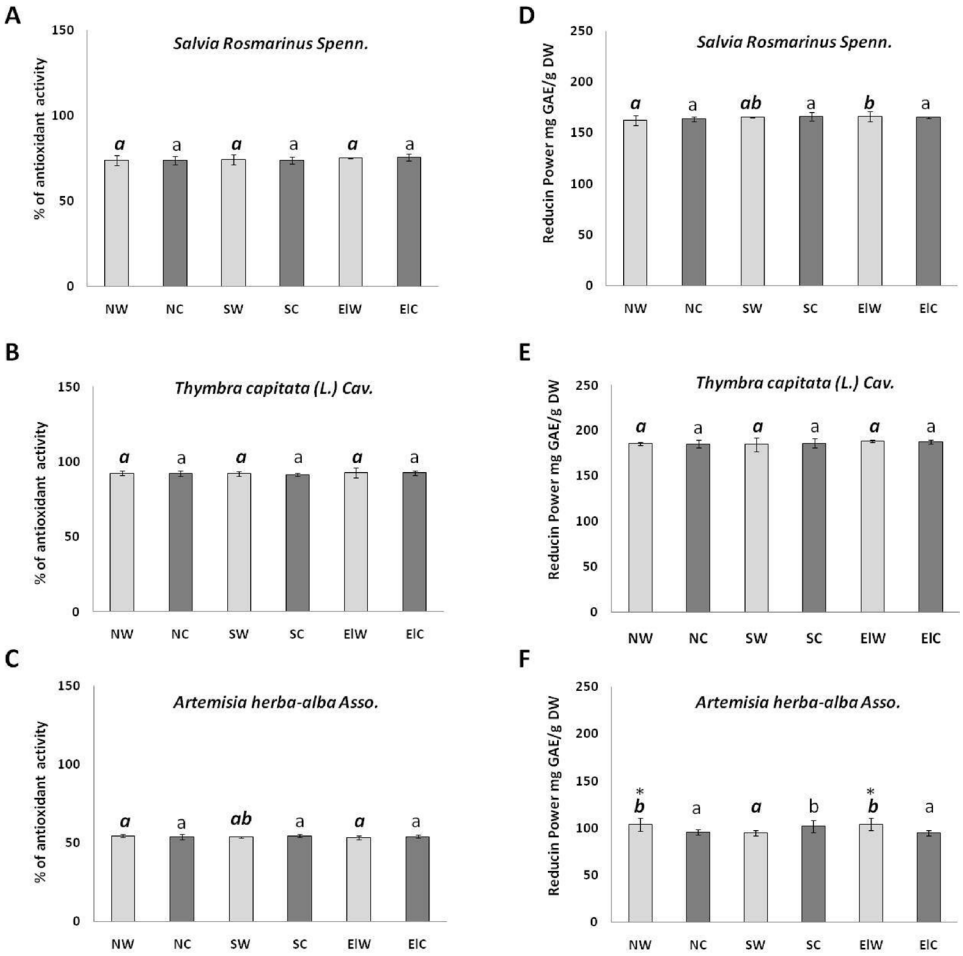


**Fig. 4** Histograms of Antioxidant Activity and Reducing Power in Leaf Extracts of Different Plants

to wild thyme (Fig. 5B). Overall, the plant maintained relatively stable anti-inflammatory activity across different provenances. Similarly, white wormwood extract followed the same trend as rosemary, showing a highly significant difference ($p<0.01$) between wild and cultivated plants (Fig. 5C).

This figure illustrates the variation in antioxidant activity and reducing power of the studied plants across all sampling sites. (A, B, C) Histograms represent the percentage of antioxidant activity in wild and cultivated rosemary, thyme, and white wormwood, respectively, collected from different regions. (D, E, F) Histograms depict the reducing power, expressed in mg of gallic acid equivalent per gram of dry weight, in wild and cultivated plants from all sampling sites. Sample size ($n=5$) refers to five individual plants and each measurement was performed in technical triplicates. Significant differences in antioxidant activity and reducing power in the leaves of wild plants—NW (Neber wild plant), SW (Seres wild plant), and ElW (El Ksour wild plant)—are indicated by bold letters (***a***, ***b***, ***c***). Differences among the cultivated plants—NC (Neber cultivated plant), SC (Seres cultivated plant), and ElC (El Ksour cultivated plant)—are indicated by regular (non-bold) letters (a, b, c) across the sampling sites. Comparisons between wild and cultivated species are reported using the following significance levels: (*) $p\leq0.05$, (**) $p\leq0.01$, and (ns) for non-significant differences. Means labeled with different letters are considered statistically different at the 5% probability level.

This figure illustrates the variation in anti-inflammatory activity of the studied plants across all sampling sites. (A) Histograms represent the variation in anti-inflammatory activity in wild and cultivated rosemary across all regions. (B) Histograms depict the variation in anti-inflammatory activity in wild and cultivated thyme. (C) Histograms show the variation in anti-inflammatory activity in wild and cultivated white wormwood. Sample size ($n=5$) refers to five individual plants and each measurement was performed in technical triplicates. Significant differences in anti-inflammatory activity in the leaves of wild plants—NW (Neber wild plant), SW (Seres wild plant), and ElW (El Ksour wild plant)—are indicated by bold letters (***a***, ***b***, ***c***). Differences among the cultivated plants—NC (Neber cultivated plant), SC (Seres cultivated plant), and ElC (El Ksour cultivated plant)—are indicated by regular (non-bold) letters (a, b, c) across the sampling sites. Comparisons between wild and cultivated species are reported using the following

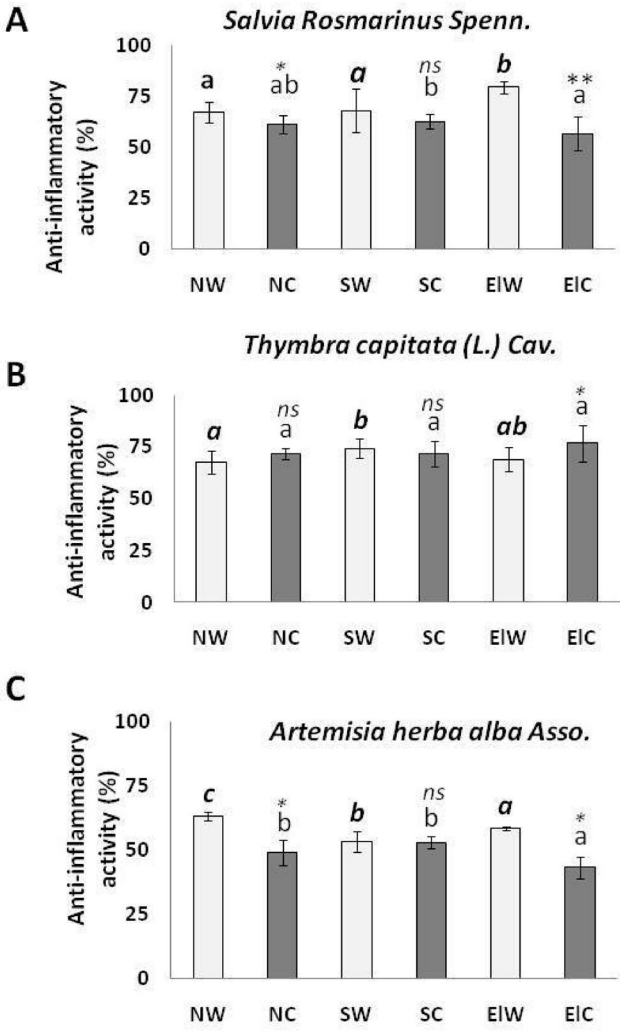


**Fig. 5** Histograms of Anti-inflammatory Activity in Leaf Extracts of Different Plants

significance levels: (*) $p \leq 0.05$, (**) $p \leq 0.01$, and (ns) for non-significant differences. Means labeled with different letters are considered statistically different at the 5% probability level.

## Discussion

MAPs have long been valued for their diverse secondary metabolites, including essential oils, polyphenols, and flavonoids, which exhibit potent antioxidant, anti-inflammatory, and antimicrobial properties (Intharuksa et al. 2024). However, their chemical composition and biological activity of these plants are highly variable and strongly influenced by environmental conditions (Shruti et al. 2024; Jaradat et al. 2025). Water availability, in particular, plays a crucial role in regulating plant physiology, including growth, stress responses, and secondary metabolite biosynthesis (Xue et al. 2018). In our study, cultivated plants exhibited significantly higher leaf water content than their wild counterparts, likely due to regular irrigation and favorable soil conditions. For example, cultivated rosemary from El Ksour retained 51.12% ± 1.80% water, compared to only 38.19% ± 2.41% in wild plants from the same region (Fig. 2A–C). Similar trends were observed in thyme and white wormwood, supporting the hypothesis that cultivated plants experience lower water stress and maintain better hydration status (Seleiman et al. 2021). These results align with previous studies showing that wild plants often display lower water content due to evolutionary adaptations to drought, such as stomatal regulation and osmotic adjustments (Emami Bistgani et al. 2024; Yang et al. 2021).

The EOY also varied significantly between wild and cultivated specimens (Fig. 2D–F), with cultivated plants generally producing higher yields. This is commonly attributed to controlled growing conditions that optimize biosynthetic pathways (Ghavam 2021). For instance, the highest EOY (0.66% ± 0.09%) was observed in cultivated rosemary from El Ksour, while the lowest yield (0.30% ± 0.07%) was recorded in wild rosemary from Neber. Similar patterns were observed in thyme and white wormwood. However, our findings also revealed exceptions —such as the lack of significant difference in EOY between wild and cultivated white wormwood in Sers—suggesting that genetic factors, in addition to environmental conditions, likely play a role in regulating oil production (Al Aboud 2024). Interestingly, the highest EOYs were recorded in cultivation sites, where abiotic stress factors (e.g., high soil salinity, increased soil electrical conductivity, and lime content) were present (Ghavam 2021). This challenges the assumption that higher essential oils production is solely due to optimal conditions and instead supports earlier findings showing that moderate abiotic stress can stimulate secondary metabolite accumulation as a defense mechanism (Selmar and Kleinwächter 2013).

The chemical composition of essential oils revealed important differences between wild and cultivated plants (Tables 2, 3 and 4), reflecting the influence of site-specific environmental stressors on secondary metabolism. For instance, wild rosemary contained higher eucalyptol concentrations (up to 63.32% in El Ksour), while cultivated plants showed elevated levels of α-pinene and camphene. These shifts may represent physiological adaptations to environmental stress: eucalyptol is known for its role in drought tolerance and herbivore defense (Alkuwayti et al. 2019), whereas α-pinene and camphene are typically associated with non-stressed metabolic profiles. Similar compositional shifts were noted in thyme and white wormwood, with wild plants generally containing higher levels of stress-related compounds such as thymol and camphor. These variations underline the importance of considering both genetic

predisposition and environmental modulation in determining chemical profiles in MAPs (Geetha and Maiti 2025).

Phenolic and flavonoid compounds are essential antioxidant agents involved in plant defense. Our results showed significantly higher PEY and TPP in cultivated plants across all species (Fig. 3A–F), likely due to improved water and nutrient availability. This finding is consistent with previous studies reporting enhanced phenolic synthesis under favorable growing conditions (*for a review*, *see* (Pratyusha 2022). However, antioxidant activity, as measured by DPPH radical scavenging, did not differ significantly between wild and cultivated samples (Fig. 4A–C), suggesting that phenolic content alone does not fully determine antioxidant capacity. This may be due to contributions from other compounds such as terpenes and flavonoids, or by synergistic interactions among them (Zhang et al. 2020). Interestingly, wild white wormwood from Seres exhibited significantly higher TF content than its cultivated counterpart (Fig. 3I), supporting the idea that certain stress conditions selectively promote flavonoid biosynthesis. This finding highlights the site-specific and compound-specific nature of secondary metabolite regulation.

Despite variations in phenolic content, antioxidant activity remained relatively stable between wild and cultivated plants (Fig. 4A–C). This suggests that while total phenolic content vary, antioxidant potential is preserved - likely due to the contributions of diverse bioactive compounds. However, anti-inflammatory activity, measured via 5-lipoxygenase inhibition, revealed significant differences between wild and cultivated plants (Fig. 5). Wild rosemary from El Ksour exhibited the highest anti-inflammatory activity (79.34% ± 2.95%), significantly higher than that of cultivated plants (56.70% ± 8.34%). A similar trend was observed in white wormwood, where wild plants demonstrated greater inhibitory effects. This enhanced anti-inflammatory potential in wild plants may be attributed to their higher concentrations of bioactive terpenes and phenolics, particularly thymol, known 5-lipoxygenase inhibitor (Taibi et al. 2024). Additionally, stress-induced metabolic pathways in wild environments likely stimulate the biosynthesis of anti-inflammatory compounds as an adaptive response (Sharma et al. 2022). These findings align with previous studies showing that wild medicinal plants often exhibit superior bioactivity compared to their cultivated counterparts due to increased secondary metabolite production under natural stress conditions (Isah 2019).

Overall, this study confirms that environmental factors play a key role in shaping the chemical and biological profiles of MAPs, although genetic factors may modulate these effects. While cultivation generally enhances growth and metabolite yield, wild plants frequently exhibit greater bioactivity due to stress-induced secondary metabolism. These findings underscore the complexity of MAPs cultivation and point to the potential trade-offs between productivity and pharmacological quality.

## Conclusion

This study highlights the significant impact of environmental conditions on the physiology, secondary metabolism, chemical composition, and bioactivity of MAPs, including *Salvia Rosmarinus Spenn.*, *Thymbra capitata (L.) Cav.*, and *rtemisia herba-alba Asso.*. Cultivated plants generally exhibited higher WC, EOY, and phenolic compound levels, likely due to favorable growing conditions. However, wild plants demonstratedsuperior anti-inflammatory activity, suggesting that environmental stressors in natural habitats may stimulate the accumulation of bioactive compounds with therapeutic potential. These findings provide valuable insights for optimizing the cultivation of medicinal plants in northwestern Tunisia. They emphasize the need to balance productivity with pharmacological quality and support strategies that promote both biodiversity conservation and the socio-economic development of rural communities, while preserving the medicinal value of native plant species.

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**Data availability** No datasets were generated or analysed during the current study.

## Declarations

**Conflict of interest** The authors declare no conflicting financial interests.

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