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Article

Evaluation of Essential Oils from *Lamiaceae* and *Myrtaceae* Families: Antifungal, Antioxidant, and Chemical Characterization for Multifunctional Purposes

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Abstract

Excessive reliance on synthetic agrochemicals has raised environmental and health concerns. Consequently, there is a growing interest in exploring natural alternatives such as plant-derived essential oils for pest and disease management. This study evaluated the essential oils extracted from *Lavandula dentata*, *Salvia rosmarinus*, and *Thymus vulgaris* (*Lamiaceae*), as well as seven *Eucalyptus* species (*Myrtaceae*). *Lavandula dentata* produced the highest essential oil yield (3.6%), followed by *Thymus vulgaris* (2.7%) and *Salvia rosmarinus* (0.66%). In the *Myrtaceae* family, the yields ranged from 0.18% to 1.94%. Chemical analysis via GC-MS and GC-FID revealed a high content of oxygenated monoterpenes, with concentrations ranging from 39.95% to 88.31%. The main constituents were 1.8 cineole, α-pinene, β-pinene, *p*-cymene and camphor except for *Thymus vulgaris* EO, where thymol (72.37%) was the dominant component. Essential oils exhibited significant antifungal activity against six phytopathogenic strains. *Thymus vulgaris*, even at low concentrations, demonstrated fungicidal activity against all the strains. Additionally, *Thymus vulgaris* essential oil showed the highest antioxidant potential, surpassing the common standard, Trolox. The present findings highlight the potential of essential oils as natural fungicides, offering an alternative to conventional synthetic fungicides. This research supports the potential use of plant-derived oils in multifunctional landscapes and integrated pest management strategies.

Keywords: essential oils; *Lamiaceae*; *Myrtaceae*; antioxidant; antifungal activity

1. Introduction

Phytopathogenic fungi represent a major global agricultural threat, causing substantial yield losses and economic hardships for farmers worldwide [1]. These pathogens affect a wide variety of crops, causing diseases that manifest as wilting, rotting, leaf spots, and other symptoms [2,3]. As these

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infections spread, they can lead to decreased crop quality and quantity [4]. Yield losses occur due to reduced crop growth, premature ripening, and compromised nutritional value, all of which directly impact farm income and food security [5]. Moreover, farmers often resort to chemical fungicides to combat these fungal diseases, which further add to production costs [6]. In the absence of effective control measures, the cumulative economic losses from fungal infections are staggering, highlighting the critical need for sustainable and eco-friendly strategies to manage these agricultural threats [7].

Essential oils (EOs) are rich in secondary metabolites—compounds produced by plants with diverse biological functions, including defense against pests and pathogens [8]. In recent years, EOs have gained attention as powerful alternatives in the battle against antibiotic, herbicide, and fungicide resistance [9]. These natural compounds contain a diverse array of bioactive constituents with antimicrobial properties, offering a sustainable solution to combat the growing problem of resistance in agriculture and healthcare [10]. EOs can play a pivotal role in eco-friendly agriculture by reducing reliance on synthetic chemicals that contribute to environmental degradation [11]. Their ability to target a broad spectrum of pathogens, while being less prone to resistance development, makes them a promising tool to address the pressing need for sustainable pest and disease management practices that safeguard both crop yields and the planet's health [12].

Beyond their aromatic qualities, EOs extracted from plants of the *Lamiaceae* family (*Lavandula dentata*, *Salvia rosmarinus* and *Thymus vulgaris*) have also been recognized for their diverse biological activities [13]. They exhibit potent antioxidant properties, helping to combat oxidative stress and protect cells from damage [14]. Additionally, these EOs have demonstrated strong antibacterial and antifungal actions, making them valuable in the fight against various microbial infections [15]. The EOs extracted from plants of the *Lamiaceae* family continue to be subjects of scientific interest and practical applications, offering a wealth of benefits to both human health and sustainable agriculture [16].

The *Eucalyptus* genus, a diverse and globally recognized group of flowering trees, is primarily native to Australia, where it thrives in a wide range of habitats [17]. However, these iconic evergreen plants have also spread to other parts of the world and are cultivated in various regions, including South America, Africa, and Southeast Asia [18]. One of the most remarkable features of the different species from *Eucalyptus* genus are their EOs, which are mainly derived from the leaves, being responsible for a distinct, invigorating aroma [19]. *Eucalyptus* EO is renowned for its numerous biological activities, making it a valuable resource in the field of natural medicine and industry [20]. It exhibits potent antioxidant properties, which can help combat free radicals and oxidative stress [21].

The present study aimed to explore the chemical composition of EOs extracted from the aerial parts of *Lavandula dentata*, *Salvia rosmarinus*, and *Thymus vulgaris*, all belonging to the *Lamiaceae* family, as well as the leaves of seven *Eucalyptus* species from the *Myrtaceae* family: *Eucalyptus camaldulensis, Eucalyptus cinerea*, *Eucalyptus grandis*, *Eucalyptus lehmannii*, *Eucalyptus leucoxylon*, *Eucalyptus saligna*, and *Eucalyptus sideroxylon*. Additionally, the study investigated the antifungal activity of these EOs against six phytopathogenic fungal strains: *Fusarium culmorum*, *F. oxysporum*, *F. proliferatum*, *Phoma* sp., *Rhizoctonia solani*, and *Sclerotinia sclerotiorum*. The antioxidant potential of the EOs was assessed using DPPH and ABTS assays.

2. Results

2.1. Essential Oil Yields and Chemical Composition

The EO yields of the selected species from the *Lamiaceae* and *Myrtaceae* families exhibited significant variation, as indicated by statistical analysis ($p < 0.05$) highlighting the variation in oil productivity. For the *Lamiaceae* family, *Lavandula dentata* yielded the highest EO content (3.6%) followed by *Thymus vulgaris* EO (2.7%) and *Salvia rosmarinus* (0.66%). In the *Myrtaceae* family, the EO yields ranged from 0.18% (*Eucalyptus grandis*) to 1.94% (*Eucalyptus camaldulensis*) (Table 1).

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Table 1. Chemical composition of EOs of Lavandula dentata (A), Salvia rosmarinus (B), Thymus vulgaris (C) and Eucalyptus species (E. camaldulensis (D), E. cinerea (E), E. grandis (F), E. lehmannii (G), E. leucoxylon (H), E. saligna (I) and E. sideroxylon (J)).

Yield percentage (%)													
				Lamiaceae									
No	Compounds	Formula	**RI**	A	B	C	D	E	F	G	H	I	J
1	Tricyclene	C10H16	**923**	0.1	0.29	0.016	-	-	-	0.012	-	0.575	0.08
2	α-Thujene	C10H16	**927**	0.02	0.11	1.005	0.052	0.005	-	0.018	0.383	-	-
3	α-Pinene	C10H16	**936**	4.35	14.42	0.951	19.199	8.16	31.96	12.69	8.054	18.2	4.381
4	Camphene	C10H16	**950**	0.49	7.86	0.358	0.242	0.23	0.546	0.23	0.211	3.9	0.136
5	Thuja-2,4(10)-diene	C10H14	**955**	0.3	-	-	0.112	0.06	0.435	0.15	0.056	0.019	0.062
6	Sabinene	C10H16	**973**	-	0.06	0.007	-	-	1.04	-	-	0.01	-
7	β-Pinene	C10H16	**977**	12.52	5.8	0.154	0.469	0.067	0.627	0.18	0.361	0.1	0.238
8	1-Octen-3-ol	C8H16O	**980**	0.02	-	0.02	-	-	0.036	0.009	-	0.073	0.027
9	Myrcene	C10H16	**989**	0.48	1.17	1.6	0.229	0.027	0.062	0.024	0.393	0.032	0.029
10	α-Phellandrene	C10H16	**1004**	0.18	0.25	0.345	1.168	0.132	0.107	0.09	3.185	0.096	0.089
11	3-Carene	C10H16	**1011**	-	0.15	0.227	-	-	0.014	-	-	0.052	-
12	α-Terpinene	C10H16	**1017**	0.14	0.42	1.638	0.128	-	0.03	-	0.111	0.032	-
13	*p*-Cymene	C10H14	**1024**	1.63	4.86	7.112	7.190	2.528	12.82	2.15	10.844	29.37	1.863
14	1,8-Cineole	C10H18O	**1031**	61.8	40.75	0.136	66.473	82.753	39.627	60.74	62.95	24.36	86.261
15	γ-Terpinene	C10H16	**1059**	0.17	0.69	7.879	0.382	0.11	0.116	0.093	0.218	0.9	0.138
16	cis-Linalool oxide	C10H18O2	**1075**	0.02	0.05	0.185	-	-	0.012	-	-	0.15	-

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17	α-Terpinolene	C10H16	**1086**	0.07	0.23	0.138	0.179	0.048	0.045	-	0.094	0.17	0.022
18	*p*-Cymenene	C10H12	**1087**	0.12	-	-	-	-	0.053	0.035	-	0.2	-
19	*o*-Guaiacol	C7H8O2	**1092**	0.08	-	-	-	-	-	0.11	-	0.15	-
20	α-Pinene oxide	C10H16O	**1097**	0.1	-	-	-	0.015	-	-	-		-
21	*trans*-Sabinene hydrate	C10H18O	**1098**	0.05	-	-	-	-	-	-	-	0.019	-
22	Linalool	C10H18O	**1099**	1.2	0.15	0.719	-	-	-	-	-	0.16	-
23	endo-Fenchol	C10H18O	**1115**	0.2	0.08	-	0.032	0.169	0.108	0.175	0.085	2.32	0.054
24	α-Campholenal	C10H16O	**1124**	0.02	0.025	-	0.021	0.024	0.282	-	0.016	0.017	0.017
25	*trans*-rose oxide	C10H18O	**1128**	0.35	0.035	-	-	-	-	0.097	-	-	-
26	*trans*-Sabinol	C10H16O	**1139**	0.03	-	-	-	0.971	-	-	0.713	3.64	-
27	*trans*-Pinocarveol	C10H16O	**1140**	2.1	-	0.007	0.525	-	4.149	-	-	-	0.532
28	Camphor	C10H16O	**1143**	0.6	7.87	0.006	-	-	0.286	15.2	-	0.34	-
29	Pinocarvone	C10H14O	**1160**	0.6	0.07	-	0.097	0.241	2.059	-	0.142	1.21	0.116
30	Borneol	C10H18O	**1166**	0.7	0.01	0.773	0.072	0.354	0.597	3.14	0.084	4.23	0.057
31	Lavandulol	C10H18O	**1168**	0.2	-	-	-	-	-	0.56	0.058	-	0.06
32	Terpinen-4-ol	C10H18O	**1177**	0.9	4.21	0.583	0.052	0.25	0.179	0.084	0.32	-	-
33	Cryptone	C9H14O	**1183**	0.5	0.52	-	0.464	-	-	0.123	-	-	-
34	*p*-Cymen-8-ol	C10H14O	**1184**	0.04	-	-	-	-	0.296	-	-	-	-
35	α-Terpineol	C10H18O	**1189**	0.16	0.06	-	0.48	0.743	0.159	0.244	0.54	1.96	0.133

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36	Myrtenol	C10H16O	**1194**	1.76	1.18	-	-	-	0.477	0.435	-	0.34	0.851
37	Verbenone	C10H14O	**1206**	1.17	-	-	0.038	-	0.233	0.32	0.036	-	-
38	*trans*-carveol	C10H16O	**1217**	0.17	-	-	-	-	0.11	-	-	0.023	-
39	*cis*-carveol	C10H16O	**1226**	0.07	0.004	-	0.011	0.018	0.089	0.079	0.009	0.13	0.022
40	Citronellol	C10H20O	**1228**	0.13	-	-	-	-	0.061	-	-	0.14	0.1
41	Pulegone	C10H16O	**1234**	-	-	-	0.035	0.068	0.038	0.192	0.049	0.1	0.092
42	Cuminaldehyde	C10H12O	**1237**	0.11	-	-	0.018	0.073	0.339	0.09	0.027	0.096	0.016
43	Piperitone	C10H16O	**1253**	0.15	-	-	-	-	0.1	0.033	0.006	-	-
44	Geranial	C10H16O	**1270**	0.015	-	0.056	-	-	-	-	-	-	-
45	Phellandral	C10H16O	**1274**	-	-	-	-	-	0.02	-	-	0.009	-
46	Citronellyl formate	C11H20O2	**1276**	0.022	-	-	-	-	-	-	-	-	-
47	Bornyl acetate	C12H20O2	**1283**	-	0.76	-	-	-	-	-	-	-	-
48	*p*-Cymen-7-ol	C10H14O	**1287**	0.01	-	-	-	-	0.018	-	-	-	-
49	Thymol	C10H14O	**1290**	-	-	72.376	-	-	-	-	0.015	-	-
50	Carvacrol	C10H14O	**1300**	0.02	0.03	-	-	-	0.018	0.014	-	0.035	0.003
51	*p*-vinylguaiacol	C9H10O2	**1317**	0.07	0.006	-	-	-	0.044	0.022	-	0.056	-
52	Myrtenyl acetate	C12H18O2	**1328**	0.005	-	-	-	-	-	-	-	0.006	-
53	Linalool	C13H2	**1336**	0.01	-	-	-	0.01	-	-	0.025	0.015	0.015

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	propanoate	2O2											
54	Piperitenone	C10H14O	**1340**	0.1	-	-	-	-	-	-	-	0.014	-
55	α-Terpinyl acetate	C12H20O2	**1347**	0.01	0.007	-	1.404	2.718	0.022	0.008	0.028	0.02	-
56	α-Cubebene	C15H24	**1351**	0.03	0.009	-	-	-	-	-	1.153	0.009	0.01
57	cis-Carvyl acetate	C12H18O2	**1362**	0.01	-	-	-	-	-	-	-	0.09	-
58	α-Ylangene	C15H24	**1369**	0.01	-	-	-	-	-	-	0.093	0.43	0.018
60	Carvacrol acetate	C12H16O2	**1373**	-	0.012	-	-	-	-	-	-	-	-
61	α-Copaene	C15H24	**1376**	0.03	0.095	-	-	-	-	-	-	0.01	-
62	β-Cubebene	C15H24	**1386**	0.02	-	-	-	-	-	-	-	0.04	-
63	β-Elemene	C15H24	**1390**	-	-	-	-	-	-	-	0.068	-	0.019
64	Methyleugenol	C11H14O2	**1401**	-	0.011	-	-	-	-	-	-	-	0.018
65	α-Gurjunene	C15H24	**1408**	0.01	0.02	-	-	-	-	0.009	0.05	-	0.314
66	E-Caryophyllene	C15H24	**1420**	0.28	6.047	2.31	-	0.026	0.012	0.029	1.243	0.39	0.033
67	β-Cedrene	C15H24	**1422**	0.04	-	-	-	-	-	0.006	0.093	-	0.044
68	β-Gurjunene	C15H24	**1431**	0.2	0.06	-	-	0.02	0.048	0.397	0.372	-	0.791
69	Aromadendrene	C15H24	**1440**	-	-	-	0.262	-	0.03	-	-	0.17	-
70	α-Himachalene	C15H24	**1445**	0.19	0.66	-	-	0.007	0.018	-	0.469	-	0.053
71	α-Humulene	C15H24	**1453**	0.19	0.02	0.103	-	-	0.028	-	-	-	0.288

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72	α-Patchoulene	C15H24	**1457**	-	-	-	0.084	-	-	0.084	-	0.07	-
73	γ-Gurjunene	C15H24	**1472**	-	-	-	-	-	-	0.009	0.056		0.024
74	γ-Muurolene	C15H24	**1476**	-	0.08	-	-	-	-	0.004	0.041	0.028	0.027
75	Ar-Curcumene	C15H22	**1482,2**	0.96	0.01	-	0.009	-	-	0.017	0.053	0.1	0.044
76	α-Amorphene	C15H24	**1482,4**	-	0.02	-	-	-	-	-	-	-	-
77	Valencene	C15H24	**1491**	0.09	0.03	-	0.011	0.018	0.033	0.079	2.612	-	1.119
78	β-Bisabolene	C15H24	**1508**	0.01	0.05	-	-	-	-	-	0.074	0.02	-
79	β-Curcumene	C15H24	**1512**	0.01	-	-	-	-	-	-	0.02		0.013
80	γ-Cadinene	C15H24	**1513**	0.35	0.11	-	-	-	-	-	-	0.05	0.015
81	δ-Cadinene	C15H24	**1523**	0.26	0.15	-	-	-	-	-	0.019	0.17	0.011
82	(E)-γ-Bisabolene	C15H24	**1532**	0.01	-	-	-	-	-	-	-		-
83	α-Calacorene	C15H20	**1540**	0.74	0.003	-	-	0.015	0.076	0.007	0.025	0.48	-
84	Germacrene B	C15H24	**1550**	-	-	-	-	-	-	-	-	-	0.078
85	β-Calacorene	C15H20	**1559**	0.11	0.004	-	0.031	-	0.028	0.087	0.056	0.08	-
86	Ledol	C15H26O	**1566**	-	-	-	0.027	-	-	0.1	0.171	0.051	0.1
87	Spathulenol	C15H24O	**1576**	-	-	-	0.039	0.01	0.619	0.27	1.113	0.23	0.19
88	Caryophyllene oxide	C15H24O	**1580**	0.28	0.194	0.456		0.026	0.1	0.63	1.403	0.11	-
89	Globulol	C15H26O	**1581**	-	-	-	0.215	-		-	-	-	0.723
90	epi-Globulol	C15H26O	**1584**	0.06	-	-	0.1	0.012	0.064	0.33	0.805	0.02	0.39

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91	Humulene epoxide II	C15H24O	**1604**	0.05	0.028	0.007	-	-	0.076	0.09	0.073	0.07	0.125
92	10-epi-γ-Eudesmol	C15H26O	**1618**	0.03	-	-	-	-	0.1	0.016	-	0.44	0.01
93	epi-1-Cubenol	C15H26O	**1625**	0.02	-	-	-	0.016	0.058	0.019	-	0.29	-
94	γ-Eudesmol	C15H26O	**1630**	-	0.012	0.012	-	-	0.034	-	0.073		0.02
95	α-Muurolol	C15H26O	**1642**	0.02	-	-	-	-	-	0.008	-	0.017	-
96	β-Eudesmol	C15H26O	**1650**	0.27	-	-	0.012	-		0.172	0.079	0.011	0.047
97	α-Cadinol	C15H26O	**1651**	0.08		0.007	-	-	0.026	-	-	-	-
98	Caryophyllenol II	C15H24O	**1659**	0.037	0.022	-	-	-		-	-	-	-
99	β-Bisabolol	C15H26O	**1672**	0.05	0.008	0.023	-	-		-	0.022	-	-
100	α-Bisabolol	C15H26O	**1682**	0.017	-	-	-	-	0.009	-	-	-	-
101	Eudesma-4(15),7-dien-1b-ol	C15H24O	**1688**	0.16	-	-	-	-		-	-	-	-
102	(2Z,6E)-Farnesol	C15H26O	**1722**	0.008	-	-	-	-		-	-	-	-
103	Chamazulene	C14H16	**1726**	0.006	-	-	-	-		-	0.029	-	0.007
104	α-Sinensal	C15H22O	**1753**	0.46	-	-	-	-		-	0.015	-	0.004
105	2-Heptadecanone	C17H34O	**1903**	0.029	0.005	-	-	-		-	-	-	-
106	Methyl hexadecanoate	C17H34O2	**1924**	-	0.007	-		-		-	-	-	
	* Yield (w/w %)			3.6 ±0.3[g]	0.66 ± 0.05[b]	2.7 ± 0.3[f]	1.94 ± 0.1[e]	1.45 ± 0.25[d]	0.18 ± 0.06[a]	1.45 ± 0.04[d]	1.17 ± 0.3[c]	0.53 ± 0.08[b]	1.33 ± 0.1[cd]

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Monoterpene hydrocarbons %	20.57	36.31	21.44	29.34	11.36	47.85	15.63	23.91	53.65	7.02
Oxygenated monoterpenes %	72.67	54.52	74.84	67.85	85.67	49.25	81.43	65.05	39.95	88.31
Sesquiterpene hydrocarbons %	2.69	7.35	2.4	0.39	0.07	0.17	0.82	6.41	1.48	2.81
Oxygenated sesquiterpenes %	2.28	0.27	0.5	0.42	0.07	1.19	1.72	3.82	1.96	1.6
Non-terpene derivatives %	0.97	1.34	0.02	1.86	2.75	0.11	0.11	0.1	0.19	0.12
Total identified %	99,18	99,79	99,2	99,86	99,92	98,57	99,71	99,29	97,23	99.86

Components are listed in their order of elution from an HP-5 capillary column, and their percentages were calculated from a flame ionization detector (FID); RI: retention indices; -: not detected; * Different letters indicate significant differences (Fisher's test at $p \leq 0.05$).

The chemical analysis of the ten EOs allowed the identification of more than 100 compounds, accounting for from 97.23 to 99.92% of the total EOs and distributed acroos five classes of terpene and non-terpene derivatives (Table 1). All EOs showed a specific richness in oxygenated monoterpenes (39.95 to 88.31%) and monoterpenes hydrocarbons (7.02 to 53.65%). A total of 85 compounds were identified in *Lavandula dentata* EO, representing 99.18% of the entire EO constituents. Oxygenated monoterpenes (72.67%) were the major portion in this oil with 1.8 cineole (61.8%), β-pinene (12.52%) and α-pinene (4.35%) being the dominant compounds. In *Salvia rosmarinus* EO, 56 chemical components were characterized which accounted for 99.79% of the total oil. Oxygenated monoterpenes (54.52%) and monoterpenes hydrocarbons (36.31%) were the two main subclasses in this oil. The prevalent constituents were 1.8 cineole (40.75%) followed by α-pinene (14.42%) and camphor (7.87%). The chemical analysis of the *Thymus vulgaris* EO showed 30 compounds representing 99.2% of the total oil. Oxygenated monoterpenes (74.84%) were the primary constituents of this oil. The major components detected in *Thymus vulgaris* EO were thymol (72.37%), γ-terpinene (7.87%) and *p*-cymene (7.11%). The chemical analysis of the EOs extracted from the leaves of the seven Tunisian *Eucalyptus* species allowed the identification of 35 compounds from *E. camaldulensis*, 33 from *E. cinerea*, 51 from both *E. grandis* and *E. lehmannii*, 55 from *E. leucoxylon*, 64 from *E. saligna* and 53 from *E. sideroxylon*, representing 99.86%, 99.92%, 98.57%, 99.71%, 99.29%, 97.23% and 99.86% of the entire EO constituents respectively. The predominant EO's constituents for *Eucalyptus* species (*E. camaldulensis, E. cinerea, E. grandis* and *E. sideroxylon*) were 1.8 cineole (39.62 to 86.26%) as oxygenated monoterpenes, followed by α-pinene (4.38 to 31.96%) and *p*-cymene (1.86 to 12.82%) as monoterpenes hydrocarbons. Camphor (15.2%) was also identified in *E. lehmannii* in addition to 1.8 cineole (60.74%) and α-pinene (12.69%). The key constituents of *E. leucoxylon* were 1.8 cineole (62.95%) followed by *p*-cymene (10.84%) and α-pinene (8.05%). The the main compound in *E. saligna* EO (29.37%) was *p*-cymene followed by 1,8- cineole (24.36%) and α-pinene (18.2%).

2.2. Antioxidant Activity

The antioxidant potential of the ten EOs were evaluated by DPPH and ABTS assays, and the results are presented in Table 2.

Table 2. Antioxidant activity of EOs of Lavandula dentata, Salvia rosmarinus, Thymus vulgaris and Eucalyptus species (E. camaldulensis, E. cinerea, E. grandis, E. lehmannii, E. leucoxylon, E. saligna and E. sideroxylon).

Different		
Essential oils	**IC_{50} (µg mL^{-1})**	
	DPPH	**ABTS**
Lavandula dentata	765.26 ±141.05^{f}	102.5 ±1.7^{h}
Salvia rosmarinus	42.32 ±3.06^{ab}	7 ±0.2^{b}

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Thymus vulgaris	3.06 ±0.04^{a}	1.5 ±0.08^{a}
Eucalyptus camaldulensis	100.1 ±6.2^{bc}	10.8 ±0.8^{c}
Eucalyptus cinerea	200.5 ±4.1^{d}	4.2 ±0.6^{ab}
Eucalyptus grandis	190.7 ±2.6^{d}	16.6 ±3.2^{d}
Eucalyptus lehmannii	562.4 ±49.1^{e}	31.7 ±1.4^{f}
Eucalyptus leucoxylon	164.08 ±25.78^{cd}	24.3 ±4.1^{e}
Eucalyptus saligna	18.5 ±1^{ab}	5 ±0.9^{ab}
Eucalyptus sideroxylon	502 ±90.9^{e}	45.3 ±2.4^{g}
Trolox	22.26 ±1.2^{ab}	33.73 ±2.8^{f}

letters indicate significant differences (Fisher's test at $p \leq 0.05$).

In both tests, DPPH and ABTS, *Thymus vulgaris* EO revealed the strongest antioxidant activity with an IC_{50} of 3.06 ±0.04 and 1.5 ±0.08 µg mL^{-1} respectively among the tested species. These values were higher than those obtained for the commonly used antioxidant standard Trolox. Then, also a high antioxidant activity was exhibited by *E. saligna* (IC_{50} of 18.5 ±1 and 5 ±0.9 µg mL^{-1}) and *Salvia rosmarinus* (IC_{50} of 42.32 ±3.06 and 7 ±0.2 µg mL^{-1}) EOs. The EOs from *E. camaldulensis, E. grandis* and *E. leucoxylon* were also active with IC_{50} values ranging from 100.1 ±6.2 to 190.7 ±2.6 µg mL^{-1} in DPPH and from 10.8 ±0.8 to 24.3 ±4.1 µg mL^{-1} in ABTS assay, respectively. Moreover, *E. lehmannii* and *E. sideroxylon* revealed moderate antioxidant activities. No significant differences between these EOs were observed in the DPPH assay. Conversely, these differences were statistically significant in the ABTS assay. Finally, the least active was the EO of *Lavandula dentata* showing IC_{50} values of 765.26 ±141.05 and 102.5 ±1.7 µg mL^{-1} in DPPH and ABTS assays respectively.

2.3. Antifungal Activity

The effects of increasing concentrations of the ten tested EOs on mycelium growth of the different fungal strains are summarized in Table 3. Most of the EOs inhibited the growth of the tested fungal strains in a dose-dependent manner.

Table 3. Antifungal activity of Lavandula dentata, Salvia rosmarinus, Thymus vulgaris and Eucalyptus species (E. camaldulensis, E. cinerea, E. grandis, E. lehmannii, E. leucoxylon, E. saligna and E. sideroxylon) EOs against phytopathogenic fungi.

		Growth inhibition pourcentage (I%)					
Essential oil	**Dose (µL mL^{-1})**	***Fusarium oxysporum***	***Fusarium proliferatum***	***Fusarium culmorum***	***Rhizoctonia solani***	***Phoma sp.***	***Sclerotinia sclerotiorum***
Lavandula dentata	0	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}
	2	28,26 ±3,8^{bA}	29,55 ±3,9^{bA}	36,96 ±6,8^{bAB}	45,10 ±6,8^{bBC}	49,02 ±12,2^{aC}	50,98 ±13,6^{bC}
	4	45,65 ±3,8^{cA}	50 ±3,9^{cA}	45,65 ±3,8^{bA}	74,12 ±6,2^{cC}	64,31 ±5,6^{bB}	80,39 ±15,1^{cC}
	6	56,52 ±10^{dA}	60 ±1,6^{dA}	77,83 ±1,3^{cB}	81,96 ±5,3^{dB}	74,90 ±1,4^{cB}	96,08 ±6,8^{dC}
	8	80 ±2^{eA}	69,55 ±3,4^{eA}	92,61 ±12,8^{dB}	100 ±0^{eB}	94,12 ±10,2^{dB}	100 ±0^{dB}
	10	100 ±0^{fB}	73,64 ±1,6^{eA}	100 ±0^{dB}	100 ±0^{eB}	100 ±0^{eB}	100 ±0^{dB}
	12	100 ±0^{f}	100 ±0^{f}	100 ±0^{d}	100 ±0^{e}	100 ±0^{e}	100 ±0^{d}
	Fongicide	100 ±0^{f}	100 ±0^{f}	100 ±0^{d}	100 ±0^{e}	100 ±0^{e}	100 ±0^{d}
MIC	(µL mL^{-1})	10	12	10	10	8	8

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MFC	(µL mL^{-1})	> 12	> 12	> 12	> 12	> 12	> 12
Salvia rosmarinus	0	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}
	2	57,61 ±4,6^{bAB}	63,86 ± 2,9^{bBC}	54,35 ± 9,2^{bA}	79,41 ± 4,2^{bD}	67,65 ± 4,2^{bC}	94,12 ± 8,3^{bE}
	4	73,91 ±9,2^{cA}	79,55 ± 9,6^{cAB}	81,74 ± 1,8^{cAB}	94,12 ± 8,3^{cC}	84,71 ± 1,7^{cB}	100 ±0^{cC}
	6	77,83 ± 1,8^{cA}	80,91 ± 1,9 ^{cA}	93,48 ± 9,2^{dB}	100 ±0^{dB}	94,12 ± 8,3^{dB}	100 ±0^{cB}
	8	100 ±0^{d}	100 ±0^{d}	100 ±0^{e}	100 ±0^{d}	100 ±0^{e}	100 ±0^{c}
	10	100 ±0^{d}	100 ±0^{d}	100 ±0^{e}	100 ±0^{d}	100 ±0^{e}	100 ±0^{c}
	12	100 ±0^{d}	100 ±0^{d}	100 ±0^{e}	100 ±0^{d}	100 ±0^{e}	100 ±0^{c}
	Fongicide	100 ±0^{d}	100 ±0^{d}	100 ±0^{e}	100 ±0^{d}	100 ±0^{e}	100 ±0^{c}
MIC	(µL mL^{-1})	8	8	8	6	8	4
MFC	(µL mL^{-1})	> 12	> 12	> 12	8	> 12	10
Thymus vulgaris	0	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}
	2	100 ±0^{b}	100 ±0^{b}	100 ±0^{b}	100 ±0^{b}	100 ±0^{b}	100 ±0^{b}
	4	100 ±0^{b}	100 ±0^{b}	100 ±0^{b}	100 ±0^{b}	100 ±0^{b}	100 ±0^{b}
	6	100 ±0^{b}	100 ±0^{b}	100 ±0^{b}	100 ±0^{b}	100 ±0^{b}	100 ±0^{b}
	8	100 ±0^{b}	100 ±0^{b}	100 ±0^{b}	100 ±0^{b}	100 ±0^{b}	100 ±0^{b}
	10	100 ±0^{b}	100 ±0^{b}	100 ±0^{b}	100 ±0^{b}	100 ±0^{b}	100 ±0^{b}
	12	100 ±0^{b}	100 ±0^{b}	100 ±0^{b}	100 ±0^{b}	100 ±0^{b}	100 ±0^{b}
	Fongicide	100 ±0^{b}	100 ±0^{b}	100 ±0^{b}	100 ±0^{b}	100 ±0^{b}	100 ±0^{b}
MIC	(µL mL^{-1})	2	2	2	2	2	2
MFC	(µL mL^{-1})	6	2	2	2	> 12	12
E. camaldulensis	0	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}
	2	32,61 ±3,7^{bB}	36,36 ±3,9^{bB}	10,87 ±7,5^{bA}	17,65 ±5,8^{bA}	85,49 ±2,9^{bC}	11,76 ±5,8^{bA}
	4	58,7 ±13,5^{cBC}	65,91 ±6,8^{cC}	36,96 ±13,5^{cA}	47,45 ±5,9^{cAB}	96,08 ±6,7^{cD}	100 ±0^{cD}
	6	75,22 ±4,7^{dA}	95,45 ±7,8^{dB}	75,22 ±2,2^{dA}	79,61 ±17,7^{dA}	100 ±0^{cB}	100 ±0^{cB}
	8	80,43 ±7^{deA}	100 ±0^{dB}	80,87 ±4,5^{dA}	100 ±0^{eB}	100 ±0^{cB}	100 ±0^{cB}
	10	86,96 ±3^{eA}	100 ±0^{dB}	100 ±0^{eB}	100 ±0^{eB}	100 ±0^{cB}	100 ±0^{cB}
	12	100 ±0^{f}	100 ±0^{d}	100 ±0^{e}	100 ±0^{e}	100 ±0^{c}	100 ±0^{c}
	Fongicide	100 ±0^{f}	100 ±0^{d}	100 ±0^{e}	100 ±0^{e}	100 ±0^{c}	100 ±0^{c}
MIC	(µL mL^{-1})	12	8	10	8	6	4
MFC	(µL mL^{-1})	> 12	> 12	12	10	> 12	4
E. cinerea	0	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}
	2	47,83 ±2,61^{bA}	55,91 ±2,8^{bB}	45,65 ±1,9^{bA}	62,35 ±2,3^{bC}	66,27 ±1,8^{bC}	82,35 ±2,35^{bD}
	4	53,04 ±3,45^{cA}	62,27 ±3,4^{cB}	59,13 ±4,1^{cB}	73,33 ±1,8^{cC}	69,02 ±1,8^{cC}	100 ±0^{cD}
	6	59,57 ±4,7^{dA}	75,45 ±1,3^{dC}	70,43 ±3,2^{dB}	91,37 ±2,9^{dD}	70,59 ±1,1^{cBC}	100 ±0^{cE}
	8	63,91 ±4,1^{dA}	82,27 ±2,7^{eC}	73,91 ±1,3^{dB}	100 ±0^{eD}	74,90 ±1,8^{dB}	100 ±0^{cD}

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	10	72,61 ±1,3^{eA}	100 ±0^{fC}	100 ±0^{eC}	100 ±0^{eC}	78,43 ±1,8^{eB}	100 ±0^{cC}
	12	76,09 ±2,72^{eA}	100 ±0^{fB}	100 ±0^{eB}	100 ±0^{eB}	100 ±0^{fB}	100 ±0^{cB}
	Fongicide	100 ±0^{f}	100 ±0^{f}	100 ±0^{e}	100 ±0^{e}	100 ±0^{f}	100 ±0^{c}
MIC	(µL mL^{-1})	> 12	10	10	8	12	4
MFC	(µL mL^{-1})	> 12	> 12	12	> 12	> 12	6
E. grandis	0	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}
	2	26,09 ±3,77^{bC}	38,64 ±6,82^{bD}	8,7 ±3^{bB}	0 ±0^{aA}	75,29 ±1,18^{bE}	0 ±0^{aA}
	4	52,17 ±7,53^{cB}	61,36 ±3,94^{cC}	23,04 ±2,26^{cA}	29,41 ±5,88^{bA}	81,18±2,35 ^{cD}	100 ±0^{bE}
	6	54,35 ±11,3^{cA}	68,64 ±2,36^{dB}	56,52 ±4,58^{dA}	68,63 ± 8,99^{cB}	85,49±2,96 ^{dC}	100 ±0^{bD}
	8	58,7 ±4,98^{cA}	80,91 ±6,25^{eB}	63,04 ±3,77^{eA}	87,45 ±4,75^{dB}	100 ±0^{eC}	100 ±0^{bC}
	10	78,26 ±3,77^{dB}	100 ±0^{fC}	73,91 ±1,3^{fA}	100 ±0^{eC}	100 ±0^{eC}	100 ±0^{bC}
	12	80,43 ±6,5^{dA}	100 ±0^{fB}	100 ±0^{gB}	100 ±0^{eB}	100 ±0^{eB}	100 ±0^{bB}
	Fongicide	100 ±0^{e}	100 ±0^{f}	100 ±0^{g}	100 ±0^{e}	100 ±0^{e}	100 ±0^{b}
MIC	(µL mL^{-1})	> 12	10	12	10	8	4
MFC	(µL mL^{-1})	> 12	> 12	> 12	10	> 12	6
E. lehmannii	0	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}
	2	23,91 ±3,8^{bB}	21,82 ±3,4^{bB}	19,57 ±10^{bB}	0 ±0^{aA}	0 ±0^{aA}	62,75 ±3,4^{bC}
	4	32,61 ±3,8^{bD}	36,36 ±3,9^{cD}	26,09 ±3,8^{bcC}	9,80 ±3,4^{bB}	0 ±0^{aA}	75,69 ±1,4^{cE}
	6	60,87 ±13^{cC}	53,64 ±4,9^{dC}	34,78 ±6,5^{cB}	91,37 ±7,6^{cD}	0 ±0^{aA}	100 ±0^{dD}
	8	65,22 ±3,8^{cdC}	58,18 ±1,6^{dB}	67,39 ±6,5^{dC}	100 ±0^{dD}	17,65 ±5,9^{bA}	100 ±0^{dD}
	10	71,74 ±7,5^{dB}	65,91 ±6,8^{eB}	73,04 ±1,5d^{eB}	100 ±0^{dC}	37,25 ±3,4^{cA}	100 ±0^{dC}
	12	71,74 ±3,8^{dB}	76,36 ±3,4^{fB}	80,43 ±2,6^{eB}	100 ±0^{dC}	41,18±11,8 ^{cA}	100 ±0^{dC}
	Fongicide	100 ±0 e	100 ±0 g	100 ±0 f	100 ±0 d	100 ±0 d	100 ±0 d
MIC	(µL mL^{-1})	> 12	> 12	> 12	8	> 12	6
MFC	(µL mL^{-1})	> 12	> 12	> 12	10	> 12	6
E. leucoxylon	0	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}
	2	49,13 ±1,3^{bA}	58,64 ±2^{bB}	49,57 ±1,9^{bA}	59,22 ±1,8^{bB}	73,73±2,96 ^{bC}	82,35 ±2,3^{bD}
	4	59,13 ±4,19^{cB}	64,55 ±3,6^{cB}	55,22 ±2,7^{cA}	75,69 ±1,8^{cC}	78,43 ±0,68^{cC}	100 ±0^{cD}
	6	64,35 ±1,9^{dB}	65,91 ±2,7^{cB}	60,43 ±1,9^{dA}	76,47 ±3,1^{cC}	85,1 ±1,36^{dD}	100 ±0^{cE}
	8	68,26 ±2,7^{deA}	67,27 ±1,3^{cA}	64,78 ±2,6^{dA}	85,1 ±2,9^{dB}	86,27±2,45 ^{dB}	100 ±0^{cC}

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	10	70 ±2,6^{eA}	100 ±0^{dB}	73,48 ±5,4^{eA}	100 ±0^{eB}	100 ±0^{eB}	100 ±0^{cB}
	12	76,52 ±3,4^{fB}	100 ±0^{dC}	73,48 ±1,9^{eA}	100 ±0^{eC}	100 ±0^{eC}	100 ±0^{cC}
	Fongicide	100 ±0^{g}	100 ±0^{d}	100 ±0^{f}	100 ±0^{e}	100 ±0^{e}	100 ±0^{c}
MIC	(µL mL^{-1})	> 12	10	>12	10	10	4
MFC	(µL mL^{-1})	> 12	> 12	>12	> 12	> 12	4
E. saligna	0	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}
	2	73,04 ±1,5^{bAB}	69,55 ±3,4^{bA}	73,04 ±1,5^{aAB}	95,69 ±7,5^{bC}	78,43 ±1,8^{bB}	100 ±0^{bC}
	4	78,26 ±2^{cAB}	75,91 ±6,3^{bcA}	85,22 ±1,5^{bC}	100 ±0^{bD}	81,18 ±1,2^{bBC}	100 ±0^{bD}
	6	95,65 ±7,5^{dB}	82,73 ±5,2^{cA}	92,17 ±6,8^{cB}	100 ±0^{bB}	96,47 ±6,1^{cB}	100 ±0^{bB}
	8	100 ±0^{d}	95 ±8,7^{d}	100 ±0^{d}	100 ±0^{b}	100 ±0^{c}	100 ±0^{b}
	10	100 ±0^{d}	100 ±0^{d}	100 ±0^{d}	100 ±0^{b}	100 ±0^{c}	100 ±0^{b}
	12	100 ±0^{d}	100 ±0^{d}	100 ±0^{d}	100 ±0^{b}	100 ±0^{c}	100 ±0^{b}
	Fongicide	100 ±0^{d}	100 ±0^{d}	100 ±0^{d}	100 ±0^{b}	100 ±0^{c}	100 ±0^{b}
MIC	(µL mL^{-1})	8	10	8	4	8	2
MFC	(µL mL^{-1})	> 12	> 12	> 12	> 12	> 12	2
E. sideroxylon	0	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}	0 ±0^{a}
	2	57,83 ±3,28^{bA}	63,18 ±1,36^{bB}	58,26 ±2,61^{bA}	60,78 ±3,4^{bAB}	79,61±0,68 ^{bC}	100 ±0^{bD}
	4	72,61 ±8,5^{cAB}	77,73 ±1,57^{cB}	76,09 ±1,99^{cB}	68,24 ±1,18^{cA}	87,06 ±2,04^{cC}	100 ±0^{bD}
	6	80,43 ±6,5^{dBC}	85,45 ±0,79^{dC}	78,7 ±0,75^{cdAB}	73,73 ±2,96^{dA}	100 ±0^{dD}	100 ±0^{bD}
	8	81,74 ±1,3^{dAB}	86,36 ±2,73^{dB}	80,43 ±1,3^{dA}	92,94 ±6,2^{eC}	100 ±0^{dD}	100 ±0^{bD}
	10	83,91 ±0,75^{dB}	90,91 ±2,08^{eC}	80,87 ±0,75^{dA}	100 ±0^{fD}	100 ±0^{dD}	100 ±0^{bD}
	12	85,22 ±1,5^{dA}	91,36 ±2,84^{eB}	85,65 ±2,26^{eA}	100 ±0^{fC}	100 ±0^{dC}	100 ±0^{bC}
	Fongicide	100 ±0^{e}	100 ±0^{f}	100 ±0^{f}	100 ±0 ^{f}	100 ±0^{d}	100 ±0^{b}
MIC	(µL mL^{-1})	> 12	> 12	> 12	10	6	2
MFC	(µL mL^{-1})	> 12	> 12	> 12	> 12	> 12	4

Means with different lowercase letters in the same column and for the same tested oil compare the difference between doses, and means with different capital letters in the same line and for the same dose compare the different sensitivities between fungi strains according to Fisher's test at $p \leq 0.05$.

The highest inhibitory activity was exhibited by the *Thymus vulgaris* EO, with total inhibition of mycelium growth at 2 µL mL^{-1} for all fungal strains. *Thymus vulgaris* EO has shown a fungicidal effect for all the tested strains with MFC values ranging between 2 and 12 µL mL^{-1} while it was fungistatic against *Phoma sp*. *Salvia rosmarinus* EO totally inhibited the growth of all fungal strains at concentrations ranging from 4 to 8 µL mL^{-1}. However, it was only fungicidal for both *R. solani* and *S. sclerotiorum* at 8 and 10 µL mL^{-1} respectively. *Lavandula dentata* EO showed moderate antifungal activity against the strains tested. The MIC values ranged between 8 and 12 µL mL^{-1}, however these

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applied doses were not lethal for all tested strains. Among *Eucalyptus* species, *E. saligna,* even at the lowest concentration (2 µL mL^{-1}), exerted a total growth inhibition and fungicidal effect on *S. sclerotiorum* strain while it showed a strong antifungal activity with inhibition percentages higher than 70% for all the others strains at the same concentration. Total inhibition was recorded for all strains when *E. camaldulensis* EO was applied at concentrations of 4 µL mL^{-1} or higher with *S. sclerotiorum*, *R. solani* and *F. culmorum* being the most sensitive strains, as indicated by their MFC ranging between 4 and 12 µL mL^{-1}. Similarly, *E. grandis* EO completely inhibited the growth of all strains at concentrations ≥4 µL mL^{-1}, except for *F. oxysporum*, which showed an inhibition percentage of 80% at the highest concentration. Among the strains, *S. sclerotiorum* and *R. solani* exhibited the highest sensitivity to *E. grandis* EO, with MFC of 6 and 10 µL mL^{-1} respectively. This indicates that both *E. camaldulensis* and *E. grandis* exert significant antifungal activity, with some variability in their effectiveness against different fungal species. More than 50% inhibition of growth was observed in all fungal strains when *E. leucoxylon* EO was used at the lowest concentration of 2 µL mL^{-1}. Complete inhibition was achieved for all strains, with MIC ranging from 4 to 12 µL mL^{-1}, except for *F. oxysporum*, which showed 76% inhibition at the highest dose of 12 µL mL^{-1}. *E. leucoxylon* EO also exhibited fungicidal effect against *S. sclerotiorum* and *F. culmorum*, with MFC of 4 µL mL^{-1} and 12 µL mL^{-1} respectively. Likewise, *E. cinerea* EO totally inhibited all strains growth at concentrations ranging between 4 and 12 µL mL^{-1} except for *F. oxysporum*. Both *S. sclerotiorum* and *F. culmorum* are the most sensitive strains with MFC of 6 and 12 µL mL^{-1} respectively. *E. sideroxylon* EO at the lowest concentration (2 µL mL^{-1}) inhibited the growth of all tested strains by approximately 60% or more, except for *S. sclerotiorum* which was totally inhibited at this concentration. Meanwhile, *Phoma sp*. and *R. solani* were fully inhibited at higher concentrations of 6 µL mL^{-1} and 10 µL mL^{-1}, respectively. *E. sideroxylon* demonstrated a fungistatic effect only on *S. sclerotiorum* strain with MFC equal to 4 µL mL^{-1}. *E. lehmannii* EO exhibited effectiveness against both *S. sclorotiurom* and *R. solani* strains with MIC values of 6 and 8 µL mL^{-1} and MFC values of 6 and 10 µL mL^{-1} respectively.

3. Discussion

Yield variation in EO production is a common challenge that arises due to several factors [22]. It is mainly influenced by the plant species or genotype, seasonal changes, and environmental conditions such as climate, soil, and geography [23–26]. The harvest stage, plant part used, and extraction method also play important roles in determining EO yield [27,28].

In this study, *Lavandula dentata* produced the highest EO content (3.6%), which aligns with the findings of El Abdali et *al.* [29], who reported a content of 3.46%. This yield is higher compared to *Lavandula dentata* studied in Tunisia (1.76%), Algeria (1.18%), Morocco (0.79 %) and Argentina 0.8% [30–33].

Golkar et *al.* [34] reported an EO yield of 0.08% for *Thymus vulgaris*. Higher yield (0.3%) was obtained by de Oliveira et *al*. [35]. According to Pavela et *al.* [36], the EO content in *Thymus vulgaris* plant parts ranged from 0.3% to 4%. The present study's findings fall within this range, with an EO yield of 2.7%. Similarly, Dinu et *al.* [37] recorded an EO yield of 2.5%.

Bayar and Akşit [38] reported an EO yield of 1% for *Salvia rosmarinus*. Çınar et *al.* [39] investigated how EO content and quality characteristics of rosemary vary based on location and harvest time, emphasizing the importance of choosing the appropriate site and harvest period for optimal oil yield. Their findings indicated that rosemary oil content ranged from 0.96 to 2.02 %. Rathore et *al.* [40] found that the EO profile of rosemary in the western Himalayan region was significantly influenced by both the harvesting season and genetic variability among accessions. Higher EO content was recorded during the autumn season (0.87%) compared to summer (0.68%) and the rainy season (0.48%). In line with these findings, the present study recorded a 0.66% EO yield for *Salvia rosmarinus*.

The yields of EOs from various *Eucalyptus* species can vary significantly, with reported percentages ranging from 0.1% to 7.3%, highlighting the wide diversity in oil content among different plants [41,42]. For example, the EO yield of *Eucalyptus camaldulensis* from Thailand has been

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documented to range between 1.07% and 2.23%, depending on the specific clones tested [43]. Similar yields have been observed in other regions, with values of 1.2% in Turkey [44] and 1.9% in Pakistan [45]. The EO yield of *Eucalyptus camaldulensis* in the present study (1.94%) is consistent with previously reported data. The EO yield of *Eucalyptus cinerea* in the present report was found to be 1.45%. In contrast, *E. cinerea* from Brazil, when extracted from both leaves and stems, produced a significantly higher yield of 5.4% [46]. In Italy, the same species yielded 2.56% when only the leaves were used [47]. Tum et al. [48] studied the impact of varying extraction times, finding that the yield of *Eucalyptus grandis* ranged from 0.5 to 0.7% which differs from our findings (0.18%). Khedhri et *al.* [49] found that *Eucalyptus lehmannii* from a Tunisian arboretum yielded 1.91%, which is higher than the yield observed in our study (1.45%). A similar observation was made for *Eucalyptus leucoxylon*, as Sebei et *al.* [50] reported a yield of 1.61%, which exceeds the yield found in our study (1.17%). Ayed et *al.* [51] reported that the EOs extracted from eight *Eucalyptus* species growing in Tunisia had yields ranging from 0.12 to 1.32%, with *Eucalyptus saligna* yielding 0.64%. Similarly, our study recorded a yield of 0.53%. Additionally, Amri et *al.* [52] reported a yield of 1.3% for *Eucalyptus sideroxylon* growing in Tunisia, which is consistent with our findings, as we also observed a yield of 1.33%.

Regarding the chemical composition of EOs, the primary constituent in all the studied species was 1.8-cineole (an oxygenated monoterpene) except in *Eucalyptus saligna* and *Thymus vulgaris*, where *p*-cymene and thymol were the dominant components respectively. Our results on chemical profiling of the *Thymus vulgaris* EO are consistent with those reported by de Oliveira et *al*. [35] concluding that the main constituents were thymol (40%), *p*-cymene (19.3%) and γ-terpinene (17.3%). Similar results were detected in *Thymus vulgaris* EO from Brasil, showing thymol (45.95%), *p*-cymene (25.11%), and γ-terpinene (8.95%) as major components [53]. Tardugno et *al*. [54] characterized three *Thymus vulgaris* EOs obtained from plants growing in Italy. The main constituents were thymol (35.84–41.15%), *p*-cymene (17.5 -21.73%), c-terpinene (15.06 - 18.42%), linalool (2.55 - 5.37%) and carvacrol (1.45 - 1.7%). Additionally, Iranian *Thymus vulgaris* EO was mainly composed of thymol (22.1%) followed by *p*-cymene (21.31%), carvacrol (13.02%), carvacrol acetate (6.72%) and linalool (5.58%) [55]. The major compounds identified within the Romanian *Thymus vulgaris* EO were thymol (55.44%), m-cymene (11.88%), γ-terpinene (5.74%) and o-cymen-5-ol (5.14%) [37]. However, *Thymus vulgaris* EO collected from Morocco showed a different chemical composition with carvacrol (59.70 %), thymol (16.5 %), and γ-terpinene (11.11 %) as main constituents [56].

The 1,8-cineole (63%) was the major compound of *Lavandula dentata* from Brazil [57], which aligns with our findings (61.8%). In Tunisia, *Lavandula dentata* EO extracted by Dammak et *al.* [31] and Touati et *al.* [58] were rich in 1,8-cineole (35 and 33.54 % respectively). In contrast, Dridi et *al.* [59] identified β-eudesmol (21.17 %), while Msaada et *al.* [60] reported linalool (47.3 %) as the predominant component. The 1,8-cineole was also observed to be the major constituent of *Lavandula dentata* cultivated in Algeria (48%), Morocco (32%), Spain (67%) and Argentina (34.33%) [32,61]. Rathore et *al.* [40] reported that *Salvia rosmarinus* EO primarily contained 1.8-cineole (45.4 - 48.1%), α-pinene (10.9 - 14%) and camphor (5.4 – 15.8%), emphasizing the variability in major EO constituents across different plant accessions. These findings are in line with the present study, where *Salvia rosmarinus* EO contained mainly 1.8 cineole (40.75%), α-pinene (14.42%) and camphor (7.87%). Additionally, Micić et *al.* [62] revealed that the most abundant compounds in *Salvia rosmarinus* EO originating from Serbia and Russia were α-pinene (23 and 17.76%), 1.8 cineole (17.79 and 23.4%) and camphor (14.39 and 17.17%) respectively. Similarly, Bayar and Akşit [38] found that the major components of Turkish *Salvia rosmarinus* EO were camphor (21.25%), 1,8-cineole (13.85%) and borneol (11.64%).

Eucalyptus EOs exhibited significant chemical variability across different geographical origins as evidenced by various studies with 1,8 cineole being the major constituent which is in line with our findings [63,64]. In Brazil, a total of 5 components were identified in *Eucalyptus camaldulensis* containing primarily 1,8-cineole (76.93%), β-pinene (11.49%), and α-pinene (7.15%) [65]. In another Brazilian study, the same plant species yielded EO from leaves with different chemical profiles, with 1,8-cineole (41.61%), α-terpineol (19.87%), and α-pinene (15.81%) as the predominant components

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[66]. However, when using the aerial parts of *E. camaldulensis* in Egypt, the main constituents shifted to spathulenol (20.84%), *p*-cymene (15.16%), and 1,8-cineole (12.01%) [67]. In Pakistan, the leaves of *E. camaldulensis* had a distinctive profile, with linalool (17%), 1,8-cineole (16%) and *p*-cymene (12.2%) being the major constituents [45]. These variations extend to other regions like Morocco, Syria, Turkey and Thailand showing *p*-cymene and γ-terpinene as the major components [43,44,68–73]. EO extracted from the leaves and stems of *E. cinerea* from Brazil, contained mainly 1,8-cineole (55.24%), α-terpinyl acetate (21.64%) and α-pinene (7.94%) [46]. In Italy, the same species yielded 1,8-cineole (67.7%), α-pinene (7.3%) and α-terpinyl acetate (5.2%) when only the leaves were used [47]. Similarly, Sebei et *al.* [50] reported that the major constituents of *E. lehmannii* growing in Tunisia were 1,8-cineole (49.07%) α -pinene (26.35%) and α-terpinyl acetate (5.64%) while *E. leucoxylon* was characterized by the dominance of 1,8-cineole (77.76%) α -pinene (5.85%) and trans-pinocarveol (3.23%). Caetano et *al*. [66] reported that *E. grandis* EO main components were 1,8-cineole (37.43%), α-pinene (36.35%), and α-terpineol (8.71%) as the predominant components. Ayed et *al.* [51] characterized *E. saligna* EO extracted from Tunisia identifying 1,8-cineole (20.36%), *p*-cymene (15.27%) and isoborneol (10.54%) as the primary compounds. In contrast, the present study found that p-cymene was the principal component in *E. saligna* EO (29.37%), followed by 1.8-cineole (24.36%) and α-pinene (18.2%). Similarly, Amri et *al.* [52] analyzed the *E. sideroxylon* EO growing in Tunisia, with the main compounds were 1,8-cineole (65.4%), globulol (7.4%) and aromadendrene (2.1%). These findings differ from those observed in the current study, where the dominant compound was 1,8-cineole (86.26%), followed by α-pinene (4.38%) and p-cymene (1.86%), highlighting a distinct chemical composition between the two studies.

Based on the EO composition, different chemotypes of *Thymus vulgaris* can be distinguished from each other, with thymol being one of the dominant chemotypes [74]. *Thymus vulgaris* is well-known to have a great antioxidant and antimicrobial ability owing to its chemical composition rich in phenolic compounds [74,75]. Previous studies concluded that the high ability to scavenge free radicals in *Thymus vulgaris* EO was related to its thymol content [34,53]. Findings of the present study indicated a highly significant antioxidant capacity of *Thymus vulgaris* EO with IC_{50} of 3.06 ±0.04 and 1.5 ±0.08 µg mL^{-1} outperforming standard Trolox (IC_{50} of 22.26 ±1.2 and 33.73 ±0.08 µg mL^{-1}) in DPPH and ABTS assays respectively. These results showed a higher antiradical capacity of the *Thymus vulgaris* EO when compared to those of Chahboun et *al*. [56] reporting IC_{50} values of 5.94 ±0.22 and 3.03 ±0.17 µg mL^{-1} in DPPH and ABTS tests respectively. Pilozo et *al.* [76] demonstrated the antioxidant profile of *Thymus vulgaris* with a radical neutralizing potential (DPPH) of IC_{50}=1.11 ±0.019 mg mL^{-1} and ferric ion reducing power of 93.05 ±0.52 mg equivalent Trolox/g. According to Golkar et *al*. [34], the biosynthetic pathway of thymol continues with *p*-cymene as an intermediate. *P*-Cymene, as a strong antioxidant component, was found in the present study to constitute 29.37% of *E. saligna* EO, which contributed to its significant antioxidant activity. However, compared to thymol and *p*-Cymene, 1,8-cineole exhibited lesser antioxidant potential. The findings of this study were compared to previously published results, all of which suggest that 1,8-cineole, the primary constituent found in the EOs of *Lavandula dentata*, *Salvia rosmarinus*, and some *Eucalyptus* species, demonstrated a moderate antioxidant potential [29,77]. In the present study, the antioxidant activity of *Salvia rosmarinus* EO (42.32 ±3.06 µg mL^{-1} DPPH assay) is within the range reported for the EOs from five different sites in Palestine, where IC_{50} values ranged from 10.23 ±0.11 to 158.48 ± 0.87 µg mL^{-1} [78]. Additionally, Eid et *al*. [79] reported a strong antioxidant activity for *Salvia rosmarinus* EO, with IC_{50} value of 22.38 ±0.7 µg mL^{-1}. The results obtained by Dammak et *al.* [31] showed that *Salvia rosmarinus* EO exhibited better antioxidant activity (IC_{50}= 11.12 µg mL^{-1}) than *Lavandula dentata* (IC_{50}= 14.03 µg mL^{-1}) using DPPH test which are consistent with our findings. El Abdali et *al.* [29] found that *Lavandula dentata* EO was able to scavenge the free radical DPPH with IC_{50} value of 12.95 µg mL^{-1}. Dridi et *al.* [59] assessed the antioxidant activity *Lavandula dentata* using three methods, with IC_{50} values of 113.29, 53.029 and 43.20 µg mL^{-1}, respectively for DPPH, ABTS and reducing power test. Several studies reported moderate antioxidant activities for *Eucalyptus* sp. EOs, with some differences depending on the species [80–82]. Limam et *al.* [83] found that EOs extracted from thirteen Tunisian

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species of the Eucalyptus genus (*globulus*, *maidenii*, *astringens*, *camaldulensis*, *lehmannii*, *melliodora*, *erythrocorys*, *gomphocornuta*, *gomphocephala*, *oxidantes*, *microcarpa*, *paniculata*, *angulosa*) exhibited a moderate antioxidant activity at concentration of 10 µg mL^{-1}, with inhibition percentages of free radical DPPH ranging from 10.75 ±1.05 to 52.69 ±4.59%. Sadraoui Ajmi et *al.* [84] revealed that *Eucalyptus cinerea* EO collected from Tunisia, exhibited a similar DPPH radical scavenging activity with an IC_{50} value of 161.59 µg mL^{-1} compared to our results (IC_{50} = 200.5 ±4.1 µg mL^{-1}). Kouki et *al.* [81] concluded that EOs from three Tunisian *Eucalyptus* species (*E. oleosa*, *E. pimpiniana*, *E. polyanthemos*) exhibited moderate antioxidant activities. Significant differences between the EOs were observed in the DPPH assay. *E. oleosa* was the most active, with an IC_{50} value of 92.179 µg mL^{-1}, followed by *E. pimpiniana* (IC_{50}= 163.593 µg mL^{-1}) and *E. polyanthemos* (IC_{50}=359.688 mg mL^{-1}). EOs from four species of *Eucalyptus* plantation in northern Thailand (*E. camaldulensis*, *E. citriodora*, *E. deglupta* and *E. urophylla*) were compared for their antioxidant activities using the DPPH method [73]. The oils exhibited antioxidant activity which varied significatively within plant species. *E. citriodora* oil rich in citronellal (68.43%) produced the best result (IC_{50}= 2.37 µg mL^{-1}) followed by *E. deglupta* (IC_{50}= 10.1 µg mL^{-1}), *E. urophylla* (IC_{50}= 19.95 µg mL^{-1}) and *E. camaldulensis* oil (IC_{50} = 25.47 µg mL^{-1}) with 1,8-cineole as major component.

Several reports have documented the antifungal effect of different species of *Thymus* against various microorganisms with thymol being mainly responsible for its antifungal activity [85–87]. In the present study *Thymus vulgaris* EO has shown a fungicidal effect for all the tested strains with MIC of 2 µL mL^{-1} and MFC varying between 2 and 12 µL mL^{-1}. While most strains were completely inhibited, *Phoma sp*. showed fungistatic response, suggesting species-specific sensitivity. In conformity with our findings, the antifungal potential of different thyme species (*Thymus convolutes*, *Thymus pectinatus* and *Thymus vulgaris*) has been demonstrated against plant pathogens including *F. oxysporum* f. sp *radicis-lycopersici*, *Phytophthora infestans*, and *R. solani* [88]. The EOs of *Thymus vulgaris* and *Thymus pectinatus* completely inhibited the growth of all the fungal strains at a dose of 4 µL per Petri dish. Conversely, other thymus species, such as *Thymus convolutes* EO showed lower antifungal efficacy, with only partial inhibition of *F. oxysporum* f. sp *radicis-lycopersici* and no effect on *R. solani* and *Phytophthora infestans* suggesting that antifungal efficacy is influenced by the chemical profile of each thymus species. The study performed by Fonseca-Guerra et *al.* [89] demonstrated that *Thymus vulgaris* EO completely inhibited the in vitro growth of *F. culmorum*, *F. equiseti*, *F. graminearum* and *F. oxysporum* isolates originating from *Chenopodium quinoa* crops at higher concentrations (MIC value of 10 µL mL^{-1}) than those required in our study,underscoring the variability in fungal sensitivity depending on isolate origin and experimental conditions. While Bounar et *al.* [90] demonstrated strong inhibition of four *Fusarium* species (*F. culmorum*, *F. equiseti*, *F. avenaceum*, and *F. moniliforme*) causing rot in potato tubers at very low concentrations (0.156-0.313 µL mL^{-1}), Divband et *al.* [91] reported higher MIC and MFC values (up to 30 mg mL^{-1}) against 20 wild-type strains of *F. oxysporum* isolates. Moghaddam and Mehdizadeh [92] reported higher doses of *Thymus vulgaris* EO (800 µL L^{-1}) to affect *F. oxysporum* and *Drechslera spicifera*, and even greater concentrations (1600 µL L^{-1}) were required to inhibit *Macrophomina phaseolina*. A comparative antifungal study showed that, among several EOs tested, only *Origanum vulgare*, *Syzygium aromaticum* and *Thymus vulgaris*, achieved total inhibitory effect at 500 µg mL^{-1} concentration. The in vivo efficacy of *Thymus vulgaris* EO (MIC of 500 ppm) was demonstrated by Pilozo et *al.* [76] reporting a significant reduction in postharvest losses caused by *Lasiodiplodia theobromae* with analogous performance to those of synthetic fungicide, increasing the shelf life of bananas and their commercial value.

Many plants, particularly those belonging to the *Lamiaceae* family are known for their antimicrobial activity, especially their EOs [62]. In our study, *Salvia rosmarinus* totally inhibited the growth of all fungal strains at concentrations ranging from 4 to 8 µL mL^{-1}. It was fungicidal for both *R. solani* and *S. sclerotiorum* at 8 and 10 µL mL^{-1} respectively. These results are consistent with those of (ElYacoubi et *al*., 2024) [94], who showed that *Salvia rosmarinus* EO achieved complete inhibition of a broad-spectrum of phytopathogenic fungi (including *F. culmorum*, *F. oxysporum*, *F. poae*, and *Helminthosporium sativum)* when applied at the highest tested concentration (1/100 v/v). Ben Kaab et

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al. [95] found that *Salvia rosmarinus* EO significantly inhibited the spore germination of *F. culmorum* (85.99%), *F. oxysporum* (100%) and *Penicillium italicum* (95.40%) at slightly higher concentration (6 µL mL^{-1}) than that used in our study. Similarly, Hussein et *al.* [96] confirmed that *Salvia rosmarinus* EO was active against six major ginseng pathogens: *Alternaria panax*, *Botrytis cinerea*, *Cylindrocarpon destructans*, *F. oxysporum*, *S. nivalis* and *S. sclerotiorum*, with MIC ranging from 0.1 to 0.5 % (v/v).

The EOs of the seven studied *Eucalyptus* species resulted in antifungal activity for all six phytopathogenic fungal strains in a dose-dependent manner. The results of the present study are consistent with those of Ayed et *al.* [51] who evaluated eight *Eucalyptus* sp. (*E. angulosa*, *E. cladocalyx*, *E. diversicolor*, *E. microcoryx*, *E. ovata*, *E. resinifera*, *E. saligna* and *E. sargentii*) against four *Fusarium* strains (*F. culmorum*, *F. oxysporum* subsp. *solani*, *F. oxysporum f. sp. matthioli* and *F. redolens*) [51]. *F. oxysporum* and *F. redolens* exhibited higher sensitivity to most of the EOs tested with complete mycelium growth inhibition at doses between 1 and 6 µL mL^{-1}. *E. cladocalyx* was the most effective EO when compared to the others, totally inhibiting mycelial growth of all fungal species studied with MIC ranging from 1 to 3 µL mL^{-1}. Amri et *al*. [52] obtained similar results with Tunisian *Eucalyptus* species (*E. citriodora*, *E. falcata* and *E. sideroxylon*) at a dose of 4 µL mL^{-1}, particularly against *Fusarium* species, which appeared more susceptible than *Bipolaris sorokiniana*. *E. citriodora* EOs demonstrated the most potent antifungal activity, completely inhibiting all strains except *B. sorokiniana* while the other two oils produced partial inhibition. Kouki et *al.* [81] revealed that *E. oleosa* EO showed the strongest inhibitory activity among three Tunisian *Eucalyptus* species (*E. oleosa*, *E. pimpiniana* and *E. polyanthemos*), fully inhibiting fungal growth at 6 µL mL^{-1}. In another study supporting these results, *E. camaldulensis* EO confirmed its fungicidal property against *Fusarium* species that affect maize with MICs and MFCs in the range of 7 to 10 µL mL^{-1} [71]. Caetano et *al.* [66] tested *Eucalyptus* EOs (*E. citriodora*, E. *camaldulensis*, E. *grandis* and E. *microcorys*) in vivo against the agent of coffee leaf rust (*Hemileia vastatrix*), reporting good antifungal activity for most species, except *E. microcorys*. Similarly, *Eucalyptus staigeriana*, *Eucalyptus globulus* and *Cinnamomum camphora* EOs were effective for both in vitro and in vivo assays against *Alternaria solani* causing early blight disease in tomato [97]. Umereweneza et *al.* [98] found that *E. melliodora* EO was the most effective among the tested species, inhibiting the growth of food spoilage fungi and aflatoxin-producing *Aspergillus* species with MICs varying from 3.3 to 8.1 mg mL^{-1} and completele inhibition of aflatoxins production at 6 and 7 µL mL^{-1}.

4. Materials and Methods

4.1. Plant Material

Plant samples were randomly collected during summer 2023 from different Tunisian regions. Aerial parts of *Lavandula dentata*, *Salvia rosmarinus* and *Thymus vulgaris* (*Lamiaceae*) and leaves from seven *Eucalyptus* species (*Myrtaceae*): *Eucalyptus camaldulensis*, *Eucalyptus cinerea*, *Eucalyptus grandis*, *Eucalyptus lehmannii*, *Eucalyptus leucoxylon*, *Eucalyptus saligna* and *Eucalyptus sideroxylon* were harvested, then were stored in a glass greenhouse for drying for 5 days (Table 4).

Table 4. Plant species, used part, period and harvesting sites.

Species	Used part	Harvesting period	Site
Lavandula dentata	Aerial parts	April 2023	Chbedda, Ben Arous
Salvia rosmarinus			Korbous, Nabeul
Thymus vulgaris		July 2023	Krib, Siliana
Eucalyptus camaldulensis	Leaves	Mach 2023	Zarniza arboreta, Sejnane
Eucalyptus cinerea			Souinet arboreta, Ain Draham
Eucalyptus grandis			Zarniza arboreta, Sejnane

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Eucalyptus lehmannii	Souinet arboreta, Ain Draham
Eucalyptus leucoxylon	Korbous arboreta, Nabeul
Eucalyptus saligna	Zarniza arboreta, Sejnane
Eucalyptus sideroxylon	Korbous arboreta, Nabeul

4.2. Essential Oil Extraction

The EOs were obtained by hydro-distillation of 100g of plant material for 3 hours using a Clevenger type apparatus (SAF Wärmetechnik LabHEAT® KM-ME, 1000 mL, SAF GmbH, Hamm, Germany). The extracted oils were dried over anhydrous sodium sulfate and stored in amber glass vials at 4°C until use.

4.3. GC-FID and GC-MS Analysis

Chemical composition of EOs was determined using Gas Chromatography coupled with Flame Ionization Detection (GC-FID) and Mass Spectrometry (GC-MS).

GC-FID analyses were assessed on an HP6890 (II) gas chromatograph (Agilent Technologies, Santa Clara, CA, USA) equipped with a flame ionization detector (FID), by using an apolar HP-5 capillary column [30 m × 0.32 mm (i.d), 0.25 µm film thickness] (Agilent Technologies). Oil diluted in hexane was injected with a split ratio of 1:50 and a flow percentage of 1.2 mL min^{-1}. The oven temperature program was: 40°C for 1 min; 40-260°C at a rate of 5°C min^{-1}; 260°C isothermally for 4 min. The temperature of the injector and the detector were maintained at 250 and 300°C, respectively.

GC–MS analyses were performed on HP 6890 N gas chromatograph coupled to an HP 5975 mass spectrometer (Agilent Technologies). The separation of volatile compounds was assessed using an HP-5MS capillary column (60 m×0.25 mm; 0.25 mm) (Agilent Technologies). The temperature of the oven ramped from 40 to 280°C at a rhythm of 5°C min^{-1}. Helium was used as a carrier gas at a flow speed of 1.2 mL min^{-1}. Scan mass range was 50-550 m/z at a sampling speed of 1 scan s^{-1}.

A standard dilution of a C_6–C_{25} n-alkanes series was prepared to calculate retention indices (*Ri*). The EO compounds were identified by comparison of their relative Ri and mass spectra with those from corresponding data (Wiley 275 L library) and/or reported in the literature [99]. The percentage of each compound was obtained from the electronic integration of its relative FID peak area without including a correction factor.

4.4. Antioxidant Activity Assays

The method of Hamdeni et *al*. [100] was used for the evaluation of the free radical scavenging activity (RSA) of EOs. Briefly, 50 µL of various dilutions of EOs were mixed with 200 µL of 0.1 mM methanolic 2,2-Diphenyl-1-picrylhydrazyl (DPPH) solution (Sigma-Aldrich, St. Louis, MO, USA). The mixture was then shaken vigorously and allowed to stand at room temperature for 30 min in the dark. The decrease in absorbance at 517 nm was measured spectrophotometrically *vs*. DPPH standard solutions. The RSA of the oil expressed as % inhibition of DPPH was calculated using the formula: % inhibition = $[(A_0 - A_s)/A_0] \times 100$, where A_0 and A_s are the absorbance values of the control and that of the sample, respectively. The concentration (µg mL^{-1}) which allowed to 50% inhibition (IC_{50}) was calculated from the graph of RSA percentage against oil concentration. All results were reported as means ± standard deviation of three measurements.

The antioxidant activity was estimated by using the 2,2′-azino-bis-3-ethylbenzthiazoline-6-sulphonic acid (ABTS) (Sigma-Aldrich) based on the reduction of $ABTS^{\bullet+}$ radicals by antioxidants present in the EOs. ABTS radical cation ($ABTS^{\bullet+}$) was produced by mixing a 7 mM ABTS solution with 2.45 mM $K_2S_2O_8$ in a ratio 1:1. The mixture was allowed to stand in the dark at room temperature for 12h before use. For the assay, the $ABTS^{\bullet+}$ solution was diluted in methanol to an absorbance of 0.7

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(±0.02) at 735 nm. Two hundred µL of $ABTS^{\bullet+}$ solution were mixed with 25 µL of the corresponding dilution of EOs. The absorbance reading was taken 30 min after initial mixing [101]. All the analyses were performed by triplicate and results were expressed as inhibition percentage of the radical cation $ABTS^{+}$ using the following formula: % inhibition ABTS = $[(A_0 - A_s)/A_0] \times 100$, where A_0 and A_s are the absorbance values of the control and that of the sample, respectively.

4.5. Antifungal Activity

The antifungal effects of EOs were tested in vitro by the direct contact method on agar. The phytopathogenic fungal strains *F. culmorum*, *F. oxysporum*, *F. proliferatum*, *Phoma sp.*, *R. solani* and *S. sclerotiorum* were provided by the Plant Protection Laboratory of the National Agriculture Research Institute of Tunisia (INRAT, Tunisia).

EOs were solubilized in a Tween 20 solution (0.1%, v/v) (Sigma-Aldrich) and later they were incorporated at increasing concentrations in Potato Dextrose Agar (PDA) medium (0, 2, 4, 6, 8, 10 and 12 µL mL^{-1}). Six mm agar plugs of each fungal strain were deposited in the center of PDA plates [81]. Negative and positive controls were carried out and each test was repeated 3 times. Incubation was performed at 24°C for 5 days. The inhibition percentage of fungal growth was determined by the following formula: Inhibition of fungal growth (I %) = [(D – Di)/ D × 100] where D and Di are the diameters of mycelial growth in control and treatment.

Minimum inhibitory concentration (MIC) is defined as the lowest dose at which there is complete inhibition of fungal growth. To establish the minimum fungicidal concentrations (MFC), the inhibited fungal disks were inoculated into PDA plates without EO and their growth was observed. After 3 days of incubation, MFC was obtained as the lowest MIC at which no growth observed in the plates after culturing [51].

4.6. Data Analysis

All of the experiments were carried out in three replicates, with the results represented as mean ± standard deviation. Statistical analyses were performed with STATISTICA software 10. The one-way analysis of variance (ANOVA) was performed to identify the effect of each treatment. The Fisher's least significant difference test at the 5% threshold was used to compare means.

5. Conclusions

The EOs extracted from various plant species, including *Lavandula dentata*, *Salvia rosmarinus*, *Thymus vulgaris* and seven *Eucalyptus* species, have shown significant promise as natural alternatives to synthetic fungicides. The chemical analysis of these EOs highlighted their rich composition of oxygenated monoterpenes and monoterpene hydrocarbons, which are key contributors to their antifungal and antioxidant properties. Among the *Lamiaceae* species, *Thymus vulgaris* EO stood out for its potent antifungal activity, exhibiting fungicidal effects against all tested fungal strains. Furthermore, *Thymus vulgaris* EO demonstrated the highest antioxidant potential, outperforming the common antioxidant standard, Trolox. The *Eucalyptus* species also presented varying levels of antifungal activity, with notable potential for controlling important phytopathogenic strains affecting crops. These findings support the hypothesis that EOs from both *Lamiaceae* and *Myrtaceae* families can serve as eco-friendly alternatives to synthetic chemicals against a broad spectrum of phytopathogenic fungi. However, differences in MIC and MFC values reported across studies highlights the influence of EO chemical composition, fungal species, inoculum densities and methodological variabilities. These disparities emphasize the need for further standardization of in vitro assays and chemical characterization of bioactive compounds to optimize their use in sustainable crop protection strategies. Additionally, further research is necessary to evaluate the field efficacy, stability, and economic feasibility of these EOs in real-world agricultural settings. Exploring their combination with other biological control agents and studying their potential for synergistic effects could also provide valuable insights for developing more robust, environmentally friendly

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pest management systems. Overall, this study contributes to the growing body of evidence supporting the role of EOs in multifunctional landscapes and their potential as effective tools in the fight against phytopathogenic fungi.

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