Chemometric Analysis of essential oils from Tunisian Plants: Unravelling the Antifungal Potential against *Botrytis cinerea*

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https://doi.org/10.4314/tjpp.v19i1.2 **(*Tunisia*)**

ABSTRACT

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The utilization of essential oils (EOs) as biofungicides holds paramount importance in sustainable agriculture, offering an eco-friendly alternative to synthetic fungicides. EOs, derived from plant sources, exhibit diverse and potent antifungal properties. This study presents a comprehensive analysis of EOs derived from Tunisian plants, focusing on their composition and antifungal properties against *Botrytis cinerea*. Gas chromatography-mass spectrometry analysis revealed diverse chemical profiles for each EO, with significant variations in major constituents. Laurel oil emerged as the most potent, exhibiting remarkable inhibitory effects ranging from 3.33% to 95.72% across different concentrations. Rosemary and sage oils demonstrated notable antifungal potential, especially at higher concentrations, while citrus oil displayed milder inhibitory effects. The hierarchical clustering of EOs based on inhibition percentages highlighted distinct clusters, emphasizing the superior antifungal properties of laurel, sage, and rosemary oils. Minimum Inhibitory Concentration (MIC) values further underscored the efficacy of rosemary, laurel, and sage oils, positioning them as promising agents for combating *B. cinerea*. Correlation analysis between volatile compounds and MIC values identified compounds with strong negative correlations, indicating potential key contributors to antifungal activity. This study contributes valuable insights into the antifungal potential of EOs, guiding future research on their mechanisms and applications in plant disease management.

Keywords: Antifungal activity; *Botrytis cinerea*; Chemometric; Essential oils

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Plant essential oils (EOs) are natural, intricate, volatile, aromatic, hydrophobic, oily liquids consisting of multiple related compounds produced in aromatic plants as secondary metabolites (Mohamed and Alotaibi 2023). These plants have been valued and utilized for their aromatic and medicinal properties since ancient times. Certain aromatic herbs, such as thyme, savory, cinnamon, cumin, rosemary, and clove, are widely used worldwide to enhance food flavors (Anil et al. 2023). Additionally, these fragrant oils are prominent ingredients in many perfumes and fragrances, like

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lavender oil, rosemary oil, lemongrass oil, and mint oil. Recently, EOs have gained popularity as major therapeutic agents in aroma and massage therapy due to their antiseptic and skin-penetrating qualities (Sharma et al. 2023). The application of EOs as bio-fungicides is of utmost significance in promoting sustainable agriculture, providing an environmentally friendly substitute for synthetic fungicides. Extracted from plant origins, EOs showcase varied and powerful antifungal characteristics, aiding in the efficient control of diseases while reducing environmental harm and fostering enduring agricultural sustainability (Anaduaka 2023).

Conventional fungicides pose potential risks to the environment and non-target organisms in aquatic systems because they affect basic biological processes not limited to fungi (Zubrod et al. 2019). Consequently, the demand for safe and effective compounds from natural sources, especially plant-derived ones, has grown in organic fruit production. Essential oils have shown promise in their insecticidal, anti-bacterial, anti-fungal, and anti-viral functions, effectively combating various pests and pathogens through the action of different functional groups present in the oils (Chang et al. 2022; Hou et al. 2022). However, it is essential to handle most EOs with caution and follow recommended guidelines, as high concentrations may have phytotoxic and cytotoxic effects (Abd-ElGawad et al. 2021).

Botrytis fungi, also known as gray mold, is a common plant pathogen that causes significant damage to a wide range of crops. This fungus infects various plant species, including fruits, vegetables, and ornamental plants, leading to decay and rot of the affected tissues. Botrytis is particularly notorious for its ability to spread rapidly under humid conditions, making it a major concern for farmers and growers worldwide. The economic impact of Botrytis can be substantial, as it can result in significant yield losses and reduced quality of agricultural products. Effective management strategies, such as proper sanitation practices and the use of fungicides, are essential to control the spread of Botrytis and minimize its economic impact on crop production.

The aim of this work is to evaluate the effect of seven EOs from geranium, rosemary, laurel, sage, citrus, nigella, and myrtle, on the inhibition percentage of *B. cinerea* mycelial growth. Additionally, we seek to gain valuable insights into the composition of these EOs through Gas Chromatography/Mass Spectrometry (GC/MS). The potential antimicrobial properties of these natural extracts hold promise for developing eco-friendly and sustainable alternatives to synthetic fungicides in agriculture. By investigating their inhibitory effects on *B. cinerea*, we hope to contribute to the advancement of crop protection strategies, promoting safer practices for both the human health and the environment.

MATERIALS AND METHODS

Plant material.

This study involved the evaluation of seven EOs obtained from different plant materials. All dried plant material were carefully chosen from a local Tunisian market based on their excellent quality to ensure the reliability and accuracy of the research findings. The botanical sources of these EOs, expressed in their Latin names, are as follows: geranium (*Pelargonium graveolens*), rosemary (*Rosmarinus officinalis*), laurel (*Laurus nobilis*), sage (*Salvia officinalis*), citrus (*Citrus sinensis*), nigella, (*Nigella sativa*) and myrtle (*Myrtus communis*).

Extraction and analysis of EOs.

As described in our previous work (Rguez et al. 2018), EOs were extracted using hydrodistillation with a Clevenger type extractor. The extraction kinetics were observed at intervals of 30, 60, 90, 120, 180, and 210 min, and the optimal duration of 3 h was determined. Subsequently, the obtained EOs were stored in a freezer at -20°C.

Gas Chromatography/Mass Spectrometry (GC/MS) analysis.

The analysis was conducted utilizing an Agilent 7890 capillary gas chromatograph (GC) equipped with an Agilent 5972 C electron impact ionization mass spectrometry detector operating at 70ev. The capillary column employed was an HP-5MS (30 m × 0.25 mm) coated with a 0.25 mm layer containing 95% dimethylpolysiloxane and 5% phenylmethyl silicone. To facilitate the analysis, the oven temperature was programmed to increase at a rate of 5°C per minute, spanning from 60 to 260°C. The carrier gas used was N60 helium, flowing at a rate of 0.9 ml/min. A 100:1 split ratio was applied, and the mass range was set from 50 to 550 m/Z with a corresponding scan duration of 1. Chemical identification was achieved by comparing the mass spectra against the Mass Spectral Registry 9th Edition NIST 2011.

In vitro antifungal activity.

Fungal strains isolation.

According to Rguez et al. (2018), the *B. cinerea* fungal strain (BCH09) was identified from grey mold-affected greenhouse-grown tomato plants. To obtain a pure strain of *B. cinerea*, tomato leaves with grey mold symptoms were chopped into small pieces and treated individually with 70% ethanol and 2% sodium hydrochloride. These leaf fragments were then equally spread onto Potato-Dextrose-Agar (PDA) growing medium. To ensure the purity of *B. cinerea* strain, the single-spore culture method was used. After 7 days of incubation at 25°C, mycelium was recovered, and conidia were collected after 10 days. Using a Malassez Hemocytometer, the concentration of conidia was adjusted to 10^6 conidia/mL, as stated in Rguez et al. (2022).

Antifungal activity of EOs.

To assess the effect of EOs on the mycelial growth of *B. cinerea*, we followed the method outlined by Maung et al. (2021). For this experiment, inverted discs measuring 5 mm in diameter and containing PDA medium were utilized. Different EOs were diluted in dimethyl sulfoxide (DMSO) at concentrations of 10, 50, 100, 250, 500, and 1000 µg/mL and then incorporated into the PDA medium. Petri dishes containing only DMSO diluted in PDA served as the negative control. After preparation, the plates were incubated at 25°C for 3 days. To calculate the inhibition percentage, the diameter of the control fungal colony and the diameter of the fungal colony treated with EOs were measured. Each tested concentration was replicated three times.

Determination of the minimal inhibitory concentration.

The determination of the minimal inhibitory concentration (MIC) of OEs extracts inhibiting 100% of *B. cinerea* was conducted following the procedure described by Rguez et al. (2022). First, the different EOs were diluted in DMSO, and then 20 µL of each oil was added to 165 µL of liquid Potato-Dextrose-Broth (PDB) medium in a 96-well plate. Subsequently, 15 µL of a conidial suspension was added to the mixture, resulting in a final range of extract concentrations from 0.078 to 1 mg/mL. The plate was then incubated in darkness at 25°C for 24 h. The absorbance was measured at 590 nm using an Ultra Microplate Reader (Synergy HT, Bio-Tek Instruments, Winooski, Vermont, U.S.). Negative and positive controls were prepared using sterile PDB medium alone and mixed with *B. cinerea* conidia, respectively.

Statistical analysis.

The reported results represent mean values obtained from a minimum of three repetitions (n = 3), unless stated otherwise. To examine the relationship between EOs and their antifungal activities, we conducted Pearson correlation analysis XLStat Pro® Version 2014.5.03 statistical software (XLStat, Paris, France). All representation and plots were performed using R (version 4.0.2).

RESULTS

EOs composition.

According to the GC/MS analysis (Fig. 1), the composition of EOs resulted in various compounds. Geranium essential oil's prominent constituents were beta-citronellol (26.97%) and geraniol (21.07%). Additionally, it contained linalol (8.57%), isomenthone (5.67%), citronellylformate (13.19%), and 8-epi-gama-eudesmol (10.19%). Minor compounds, including beta-bourbonene (0.84%), trans-caryophyllene (0.83%), and ledene (1.61%), further enriched its chemical profile. On the other hand, citrus oils featured high limonene content (81.5%), accompanied by linalool (4.1%), 4-terpineol (4.10%), and alpha-terpineol (1.00%), enhancing its aromatic complexity. The composition of nigella oils included significant linalool (41.43%), *p*-cymene (26.99%), and alpha-thujene (7.25%). Meanwhile, laurel oils were distinguished by 1,8-cineole (48.18%), sabinene (14.44%), and beta-fenchyl alcohol (7.34%). In rosemary EOs, major compounds like alpha-pinene (13.46%), camphene (4.71%), verbenene (8.66%), and 1,8-cineole (42.14%) stood out. Notable constituents also included *p*-cymene (1.21%), trans-caryophyllene (4.61%), camphor (11.69%), and endo-borneol (3.57%). Minor compounds present in smaller amounts were alpha-terpineol (1.66%), alpha-fenchyl acetate (1.55%), and trans-beta-ocimene (0.97%). Sage oil's composition encompassed alpha-pinene (54.98%), 1,8-cineole (30.49%), and cymene (1.75%), along with minor compounds like terpinen-4-ol (0.37%) and trans-caryophyllene (1.29%). Lastly, myrtle EOs were predominantly composed of alpha-pinene (56.91%) and 1,8-cineole (28.05%), giving it its characteristic aroma. Significant compounds included camphor (0.14%), trans-caryophyllene (1.33%), and lavandulyl acetate (1.07%), contributing to its aromatic complexity. Minor components like beta-fenchyl alcohol (2.08%), linalool (1.78%), and alpha-terpinolene (0.71%) further enriched the oil overall chemical composition. The oils also contained trace amounts of various compounds, including germacrene B (0.08%), beta-myrcene (0.14%), and alpha-humulene (0.17%).

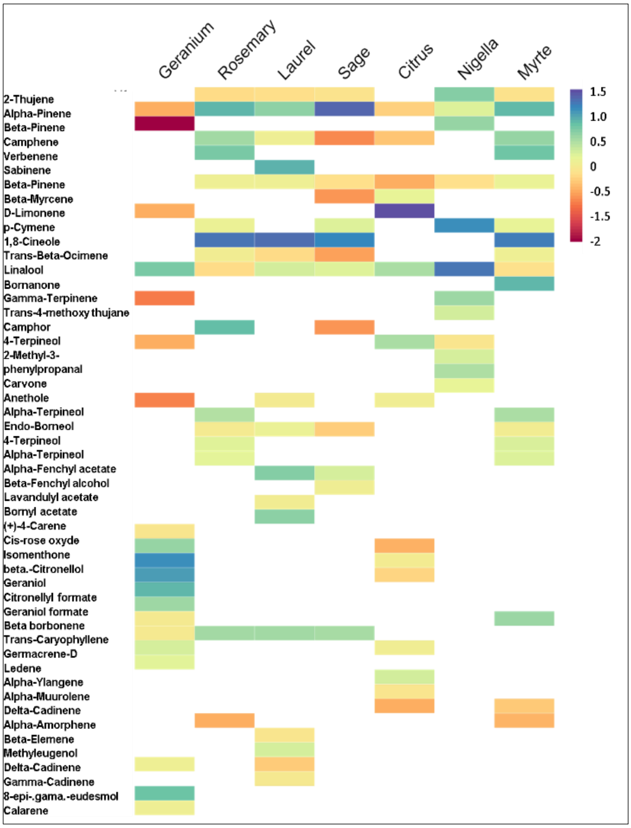

Fig 1. Essential oil composition heatmap. Values were converted to decimal log.

Inhibition of *B. cinerea* growth by different EOs.

Fig. 2 presents the percentage of inhibition of *B. cinerea* growth at various concentrations of different EOs tested. In our investigation into the antifungal properties of EOs from various Tunisian plants against *B. cinerea*, significant variations in inhibitory effects were observed at the different concentrations. Laurel oils consistently stood out, showcasing the highest antifungal activity across the board. Notably, Laurel demonstrated impressive inhibition percentages ranging from 3.33% at the lowest concentration (10 µg/mL) to a striking 95.72% at the highest concentration (1000 µg/mL). This robust performance suggests that Laurel oil possesses potent inhibitory effects against *B. cinerea* growth.

Rosemary and sage EOs also exhibited notable antifungal potential, particularly at higher concentrations. Rosemary, for instance, displayed a considerable increase in inhibition from 2.42% at 10 µg/mL to a substantial 94.12% at 1000 µg/mL. Similarly, sage showed a noteworthy escalation in inhibition percentages from 3.28% to 93.64% over the same concentration range. These findings underscore the effectiveness of these EOs as potential agents against *B. cinerea*.

Conversely, citrus EOs displayed comparatively lower inhibition percentages across all concentrations, suggesting a milder antifungal effect. This observation prompts further exploration into the specific compounds within citrus EOs and their potential roles in fungal inhibition. The consistent performance of laurel EOs, coupled with the varying degrees of efficacy among the tested oils, opens avenues for future research on the mechanisms and active compounds responsible for their antifungal properties.

The hierarchical classification of EOs based on their inhibition percentages, as illustrated in Fig. 2, reveals distinct clusters that provide valuable insights into their antifungal activities. The first cluster encompasses the oils with the least pronounced inhibitory effects, namely those of citrus and geranium. This suggests a lower efficacy of these oils against the target pathogen compared to others in the study. The second cluster includes nigella and myrtle EOs, indicating a moderate level of antifungal activity. Finally, the third cluster comprises the EOs with the highest inhibitory potential, namely those of laurel, sage, and rosemary. This classification emphasizes the robust antifungal properties of laurel, sage, and rosemary EOs, positioning them as promising candidates for further exploration and potential applications in the management of *B. cinerea*-induced disease in agricultural and therapeutic contexts. The hierarchical clustering provides a succinct visualization of the oil relative efficacy, aiding in the identification of key candidates for future research and practical utilization.

Minimum inhibitory concentrations of various EOs.

The Minimum Inhibitory Concentrations (MIC) of EOs from different Tunisian plants against *B. cinerea* were determined in this study (Fig. 3). The MIC values represent the concentration at which the EOs completely inhibited the growth of the fungus. Among the oils tested, rosemary, laurel, and sage EOs exhibit the lowest MIC values at 125 µg/mL, suggesting a higher potency and a lower concentration required to inhibit the growth of target pathogen. This indicates their potential as effective antifungal agents. Citrus and geranium EOs have higher MIC values (1000 µg/mL), indicating a comparatively lower potency. Notably, nigella and myrtle EOs show intermediate MIC values at 250 µg/mL. These MIC results complement the antifungal inhibition percentages, reinforcing the potential of laurel, rosemary, and sage as strong candidates for inhibiting *B. cinerea* growth at lower concentrations. Further exploration into the specific compounds responsible for these inhibitory effects could enhance our understanding of their antifungal mechanisms and contribute to practical applications in plant disease management.

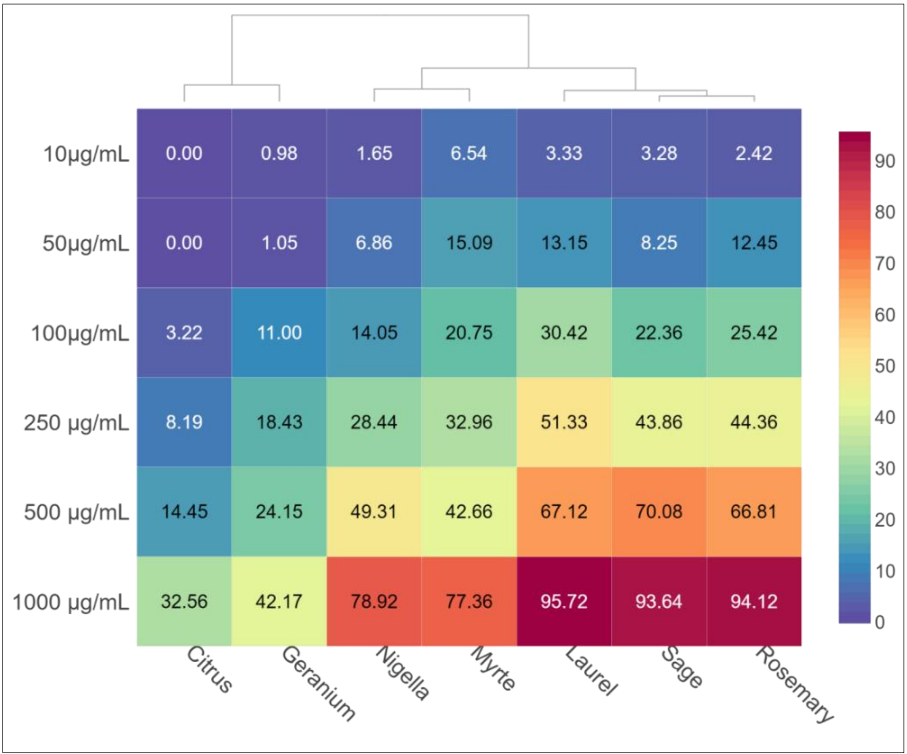

Fig. 2. Hierarchical classification heatmap of inhibition concentrations of various EOs in the presence of *B. cinerea*.

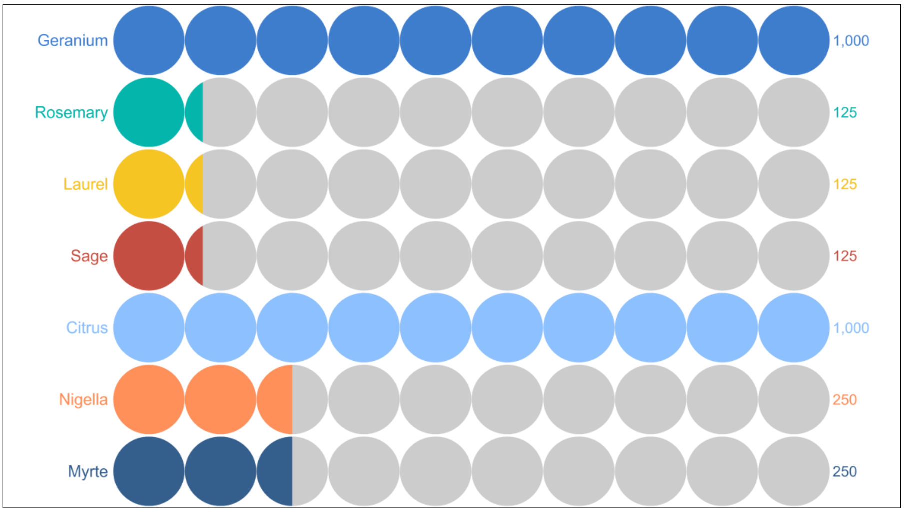

Fig. 3. Minimum Inhibitory Concentrations of EOs expressed in µg/mL.

Correlation analysis of volatile compounds in EOs against *B. cinerea*.

The correlation analysis of volatile compounds in the studied EOs with Minimum Inhibitory Concentration (MIC) values has revealed significant associations, shedding light on the potential antifungal efficacy of individual components. Compounds such as beta-pinene, beta-myrcene, *d*-limonene, gamma-terpinene, alpha-terpineol, beta-bourbonene, trans-caryophyllene, and 4-terpineol exhibit a strong negative correlation close to -1, suggesting a robust inverse relationship where higher concentrations are linked to lower MIC values, indicative of potent antifungal activity against *B. cinerea*. Conversely, compounds with strong positive correlations, including endo-borneol, alpha-terpineol 2, alpha-fenchyl acetate, isomenthone, beta-citronellol, geraniol, *d*-germacrene, delta-cadinene, alpha-amorphene, and delta-cadinene 2, showed a direct relationship with higher MIC values. Compounds like 1,8-cineole and alpha-pinene exhibited a moderate negative correlation, emphasizing their potential contributions to antifungal activity. This nuanced understanding of the correlation between specific volatile compounds and MIC values provides valuable insights for further exploration and the development of targeted antifungal strategies.

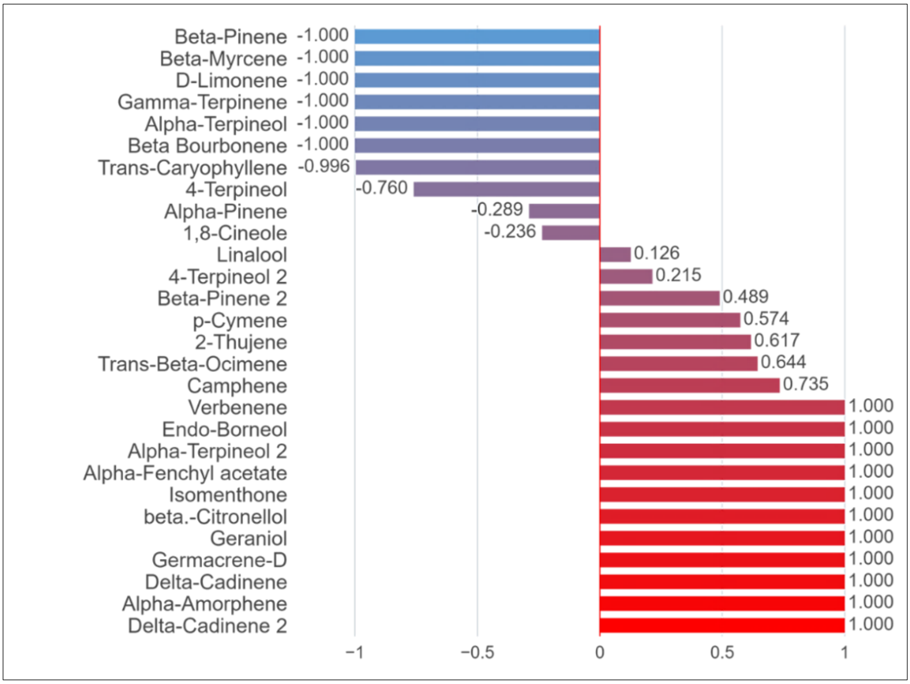

Fig. 4. Pearson correlation coefficients between volatile compounds and minimum inhibitory concentrations of EOs against *B. cinerea*. Negative correlations tending towards -1 are indicated in blue, representing negative correlations, while positive correlations tending towards 1 are indicated in red, representing positive correlations.

DISCUSSION

The gas chromatography-mass spectrometry (GC/MS) analysis provided a comprehensive understanding of the composition of the EOs investigated in this study. Geranium EOs exhibited a rich chemical profile, with beta-citronellol and geraniol as major constituents, in agreement with findings reported by Azhdarzadeh et al. (2018). Citrus EOs, characterized by a high limonene content, also featured linalool, 4-terpineol, and alpha-terpineol, aligning with the aromatic complexity reported by Farhat et al. (2020). Nigella EOs displayed a significant presence of linalool, *p*-cymene, and alpha-thujene, consistent with results from in Algerian *Nigella sativa* (Benkaci-Ali et al. 2007). Laurel oil distinctive composition included 1,8-cineole, sabinene, and beta-fenchyl alcohol, mirroring the findings of Grati-Affes et al. (2023). Rosemary EOs showed cased alpha-pinene, camphene, verbenene, and 1,8-cineole as major components, with agreement found in the results of Yeddes et al. (2022). Sage EOs, in line with Rguez et al. (2019), exhibited alpha-pinene, 1,8-cineole, and cymene as its primary constituents. Myrtle EOs, dominated by alpha-pinene and 1,8-cineole, demonstrated a characteristic aroma, and its composition correlated with the findings of Grati-Affes et al. (2023). The consistent alignment of our results with existing literature underscores the reliability and reproducibility of the essential oil compositions obtained through GC/MS analysis.

Essential oils play a pivotal role in biological fungal treatment due to their diverse and potent antifungal properties (Wu et al. 2023). These natural compounds, derived from plant sources, offer a sustainable alternative to synthetic fungicides, reducing environmental impact (Corrêa and Ferreira 2023). The complex composition of EOs allows for a multifaceted approach, targeting various stages of the fungal life cycle and minimizing the risk of resistance development (Prakash et al. 2024). Additionally, EOs often exhibit low toxicity to non-target organisms, making them promising candidates for eco-friendly and effective biological control strategies against fungal pathogens (Ferraz et al. 2022; Giunti et al. 2022). In our study, laurel EOs have been found to have antifungal properties against various fungal strains (Belasli et al. 2020; Lobos et al. 2021; Grati Affes et al. 2023). The EOs from Chilean laurel showed important antifungal activity against *Candida albicans*, a human pathogenic yeast strain, with a minimum inhibitory concentration of 64 µg/mL (Lobos et al. 2021). Laurel EOs also exhibited inhibitory effects on the mycelial growth of *Alternaria alternata*, a fungal pathogen, both in vitro and in vivo (Grati-Affes et al. 2023). The EOs from Algerian laurel (*Laurus nobilis*) demonstrated antifungal activity against *Aspergillus flavus*, inhibiting its growth and aflatoxin B1 production (Belasli et al. 2020). Additionally, laurel EOs showed antifungal activity against *Fusarium oxysporum* and *Pestalotiopsis funerea*, which are common fungal pathogens causing diseases in conifer seedlings (Kara et al. 2020). These findings suggest that laurel EOs have potential as an antifungal agent.

Rosemary EOs showed antifungal effects against *F. oxysporum*, inhibiting its growth and disease development (Mekonnen et al. 2019). It was found to be rich in monoterpenes, with 1,8-cineole, camphor, and alpha-pinene as major constituents (Kaab et al. 2019). Additionally, the EOs from rosemary exhibited antifungal activity against *C. albicans*, inducing cell death and inhibiting hyphal morphogenesis and biofilm formation (Shahina et al. 2022). Sage EOs, on the other hand, showed allelopathic effects against weed seeds and had antiproliferative activity on melanoma cell lines (da Silva Bomfim et al. 2020). These studies suggest that both rosemary and sage EOs have potential as natural antifungal agents.

In conclusion, our investigation into the essential oil composition and antifungal properties against *B. cinerea* provides valuable insights into potential natural alternatives for disease control. Laurel, rosemary, and sage EOs, characterized by distinct chemical profiles, demonstrated potent inhibitory effects on the fungal pathogen. The hierarchical clustering reinforced the superior antifungal properties of these EOs, guiding their selection for further research and practical applications. Minimum Inhibitory Concentrations highlighted the concentration at which complete inhibition of *B. cinerea* growth occurred, emphasizing the potency of rosemary,

laurel, and sage EOs. Correlation analysis identified key volatile compounds with strong negative correlations, suggesting their pivotal role in antifungal efficacy. Overall, this study contributes to the understanding of EOs as effective and sustainable tools for biological control of fungal pathogens, paving the way for future investigations into the specific mechanisms and applications of these natural compounds in agriculture and beyond.

RESUME

Rguez S., Grati-Affes T., Yeddes W., Hammami M. et Hamrouni-Sellami I. 2024. Analyse chimiométrique des huiles essentielles de plantes tunisiennes: Décryptage du potentiel antifongique contre *Botrytis cinerea*. Tunisian Journal of Plant Protection 19 (1): 13-26.

L'utilisation d'huiles essentielles comme biofongicides revêt une importance capitale dans l'agriculture durable, offrant une alternative écologique aux fongicides synthétiques. Les huiles essentielles, issues de sources végétales, présentent des propriétés antifongiques diverses et puissantes. Cette étude propose une analyse exhaustive d'huiles essentielles (HEs) provenant de plantes tunisiennes, en se concentrant sur leur composition et leurs propriétés antifongiques contre *Botrytis cinerea*. L'analyse GC-MS (chromatographie en phase gazeuse couplée à la spectrométrie de masse) a révélé des profils chimiques variés pour chaque HE, avec des variations significatives des constituants majoritaires. Les huiles essentielles du laurier sont apparues comme les plus puissantes, présentant des effets inhibiteurs remarquables allant de 3,33% à 95,72% selon les concentrations. Les huiles essentielles du romarin et de la sauge ont démontré un potentiel antifongique notable, en particulier à des concentrations plus élevées, tandis que les huiles des agrumes ont montré des effets inhibiteurs plus faibles. La classification hiérarchique des HEs basée sur les pourcentages d'inhibition a mis en évidence des groupes distincts, soulignant les propriétés antifongiques supérieures des huiles essentielles du laurier, de la sauge et du romarin. Les valeurs de la Concentration Minimale Inhibitrice (CMI) ont encore souligné l'efficacité des huiles essentielles du romarin, du laurier et de la sauge, les positionnant comme des agents prometteurs pour la lutte contre *B. cinerea*. L'analyse de corrélation entre les composés volatils et les valeurs de la CMI a identifié des composés présentant de fortes corrélations négatives, indiquant des contributeurs potentiels clés à l'activité antifongique. Cette étude apporte des connaissances précieuses sur le potentiel antifongique des huiles essentielles, guidant les recherches futures sur leurs mécanismes et leurs applications dans la gestion des maladies des plantes.

Mots clés: Activité antifongique, *Botrytis cinerea*, chémométrie, huiles essentielles

ملخص

رقاز، صفا وتيسير قراتي-عفّاس ووليد يدعس ومجدي حمامي وابتسام حمروني-سلامي. 2024. تحليل كيميائي قياسي للزيوت الأساسية من النباتات التونسية: كشف الإمكانات المضادة للفطريات ضد الفطر *Botrytis cinerea*.
Tunisian Journal of Plant Protection 19 (1): 13-26.

استخدام الزيوت الأساسية كمضادات للفطريات الحيوية يحمل أهمية قصوى في الزراعة المستدامة، حيث يقدم بديلًا صديقًا للبيئة للمبيدات الفطرية الاصطناعية. تتمتع الزيوت الأساسية، المستخلصة من مصادر نباتية، بخصائص مضادة للفطريات متنوعة وفعّالة. يقدم هذا البحث تحليلًا شاملاً للزيوت الأساسية المستخلصة من نباتات تونسية، مركزًا على تركيبها وخصائصها المضادة للفطريات ضد الفطر *Botrytis cinerea*. أظهر تحليل الكروماتوغرافيا الغازية - الطيف الكتلي للزيوت تشكيلات كيميائية متنوعة لكل زيت أساسي، مع اختلافات كبيرة في المكونات الرئيسية. ظهر زيت الغار كالأكثر فعالية، حيث أظهر تأثيرات تثبيطية جيدة تتراوح بين 3.33% إلى 95.72% عند تراكيز مختلفة. أظهرت زيوت

الإكليل والمريمية والمردقوش إمكانات مضـــادة للفطريات ملحوظة، خاصـــة في تراكيز أعلى، في حين أظهرت زيوت الحمضيات تأثيرات تثبيطية أخف. أبرز تجميع الزيوت الأساسية بناءً على نسب التثبيط تجمعات متميزة، مؤكداً التفوق في خصـائص مكافحة الفطريات للزيوت الأسـاسـية للإكليل و المريمية والمردقوش. قِيم التركيز التثبيطي الأدنى أكدت بشـكل إضافي فعالية الزيوت الأساسية للإكليل والغار والمردقوش، موضحة أنها واعدة في مكافحة الفطر *B. cinerea*. وأظهر تحليل معامل الارتباط بين المركبات الأساسية وقِيم التركيز التثبيطي الأدنى وجود مركبات ذات علاقات سـلبية قوية، مشيرًا إلى أنها قد تكون من المساهمين الرئيسيين في النشاط المضاد للفطريات. يقدم هذا البحث رؤى قيمة حول الإمكانيات المضادة للفطريات للزيوت الأساسية، مما يوجه البحث المستقبلي حول آلياتها وتطبيقاتها في إدارة أمراض النباتات.

كلمات مفتاحية: زيوت أساسية، قياس كيميائي، نشاط مضاد للفطريات، *Botrytis cinerea*

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