Journal of Plant Production and Sustainability
DOI: https://doi.org/10.63072/jpps.25010
Volume 1, Issue 2, 2025, Pages 38-49
ISSN: 3135-7423 (Online)
https://jplantps.org/

RESEARCH PAPER

Comparative *in vitro* evaluation of antimicrobial potential of ethanolic leaf extracts from different *Artemisia* species against infection-causing pathogens

Hina Fazal[1], Iram Fatima[1], Gohar Rahman[1], Abdul Haq[1], Nisar Ahmad[2]*, Arshad Iqbal[2] and Mohammad Ali[2]

[1]Pakistan Council of Scientific and Industrial Research (PCSIR) Laboratories Complex, Peshawar 25120, Pakistan
[2]Center for Biotechnology and Microbiology, University of Swat, Swat-19200, Pakistan

*Correspondence author's email: ahmadn@uswat.edu.pk

Abstract

Artemisia species are commonly administered in polyherbal drugs to treat various infectious diseases. The main component of Artemisia species is artemisinin that showed a multi-dimensional biological activity. Focusing on the therapeutic potential, the aim of this study was to provide scientific evidence for the antimicrobial activity of six *Artemisia* species *viz. Artemisia scoparia, Artemisia persica, Artemisia arborescens, Artemisia absinthium, Artemisia vulgaris* and *Artemisia nilagirica.* Leaf extracts were prepared using ethanol and then antimicrobial assay was performed following agar well diffusion method. Eight bacterial strains were grown on nutrient agar, however, *C. albicans* was grown in potato dextrose agar (PDA) followed by required incubation. Azithromycin, Ciprofloxacin and Clotrimazole were used as standard antibiotics for antimicrobial activity. Results revealed that all six Artemisia leaf extracts exhibited measurable antimicrobial activity, though with varying potency across species. *A. persica* showed the strongest and broadest activity, producing the largest inhibition zones (up to 20.5 mm), particularly against *E. coli*, *B. subtilis*, *K. pneumoniae*, and *S. mutans*. *A. scoparia* and *A. arborescens* also demonstrated broad-spectrum inhibition, with moderate activity across all tested strains. *A. absinthium* and *A. vulgaris* displayed comparatively lower but consistent antimicrobial effects, with the greatest activity observed against *P. aeruginosa* and *S. aureus*, respectively. *A. nilagirica* exhibited selective activity, showing strong inhibition of *S. aureus* (17 mm) but no effect on *P. aeruginosa*, *S. typhi*, or *C. albicans*. Overall, the findings indicate that Artemisia species possess varying degrees of antimicrobial potential, with *A. persica* emerging as the most effective across the tested microorganisms. Hence, it can be concluded that the selected species can be used as a potential source of antimicrobial agents in food and pharmaceutical industries.

Keywords: Agar-well diffusion assay, Antimicrobial, *Artemisia*, Bacteria, *K. pneumonia*, Medicinal plants, *S. mutans*

Citation: Fazal, H., Fatima, I., Rahman, G., Haq, A., Ahmad, N., Iqbal, A., & Ali, M. (2025). Comparative *in vitro* evaluation of antimicrobial potential of ethanolic leaf extracts from different Artemisia species against infection-causing pathogens. *Journal of Plant Production and Sustainability, 1*(2), 38–49. https://doi.org/10.63072/jpps.25010

Introduction

Plants have long been recognized as valuable sources of novel therapeutic compounds and have played a crucial role in traditional medicine systems (Parameswari et al., 2019; Khan et al., 2020). Bioactive plant-derived compounds exhibit significant antimicrobial and antitoxin properties, making them reliable candidates for use as anti-infective agents or as adjuncts to conventional therapies (Blaszyle & Holley, 1998). Nonetheless, it is essential to thoroughly investigate the pharmacological properties of these natural mixtures to understand their effects on biological systems (Viegas & Bolzani, 2006; Ushimaru et al., 2007). It is estimated that around 80% of the world's medicines are derived from plant-based bioactive components (Owolabi et al., 2007). Due to their therapeutic potential, medicinal plants continue to attract considerable interest in modern pharmacological research and drug discovery (Butler, 2004). Their use offers several advantages over synthetic drugs, particularly in addressing multi-drug resistance and minimizing adverse side effects, as herbal remedies are generally regarded as safer and less toxic alternatives (Keshebo et al., 2016; Nisar et al., 2017).

Bacterial infections remain among the leading causes of mortality worldwide (Wu et al., 2022). Antibiotic therapy has long been a cornerstone of treatment; however, the misuse and overuse of antibiotics have accelerated the emergence of multidrug-resistant (MDR) bacterial strains (Prestinaci et al., 2015; Crits-Christoph et al., 2022). As a result, many conventional antibiotics and traditional treatments are becoming increasingly ineffective (Styers et al., 2006). Antimicrobial resistance (AMR) has therefore evolved into a serious global public health concern (Dupuis et al., 2022). It is projected that by 2050, infections caused by antibiotic-resistant pathogens could be responsible for approximately 10 million deaths annually, posing not only a health crisis but also a

significant economic burden (McEwen & Collignon, 2018; Antimicrobial Resistance Collaborators, 2022). The rise of MDR bacteria has severely restricted the clinical utility of existing antibiotics, as effective treatment options are diminishing or, in some cases, no longer available (Magiorakos et al., 2012). To address this challenge, the World Health Organization (WHO) released a global priority list in 2017 identifying antibiotic-resistant bacteria that pose the greatest threat to human health (De Oliveira et al., 2020). Despite the urgent need for new antibiotics, the discovery and development process remains hindered by high costs (often in the hundreds of millions of dollars), long development timelines (averaging around ten years), and limited commercial incentives only 17 novel antibiotics were approved between 2010 and 2021 (Safir et al., 2020; Berini et al., 2022). Consequently, there is growing scientific interest in exploring alternative therapeutic sources. Plant-derived natural products, with their rich diversity of bioactive compounds, have emerged as promising candidates for combating antibiotic-resistant pathogens (Subramani et al., 2017; Fatima et al., 2022).

The Artemisia genus, which includes more than 500 species of herbs and shrubs distributed across the globe, represents the largest group within the family Asteraceae (Sengul et al., 2011; Ivănescu et al., 2021). Many species of this genus have long been valued in traditional medicine for their wide range of healing properties. They are rich in diverse secondary metabolites such as essential oils, flavonoids, organic acids, and lactones that exhibit significant pharmacological activities, including antimalarial, hepatoprotective, anticancer, and anti-inflammatory effects (Bora & Sharma, 2011; Abad et al., 2012; Ekiert et al., 2021; Shinyuy et al., 2023). Among Artemisia species, *Artemisia scoparia*, *Artemisia persica*, *Artemisia arborescens*, *Artemisia absinthium*, *Artemisia vulgaris*, and *Artemisia nilagirica*, have a known history of geographical diversity and traditional use in different regions (Sengul et al., 2011; Russo et al., 2020; Bidgoli et al., 2021; Sharifi et al., 2022). These are commonly used to treat infections such as inflammation, cough cold, malaria, fever, influenza, and diabetes, digestive disorders and wound healing (Liu et al., 2009; Sharifi et al., 2022; Vitale et al., 2022). The demand for alternative antimicrobial agents, especially those derived from natural sources, has driven extensive research to evaluate plant-based drugs for combating infectious diseases (Vieira et al., 2017; Szczepanik et al., 2018; Guan et al., 2019). Antimicrobial potential of some Artemisia species have been reported in previous literature (Behbahani et al., 2017; Vieira et al., 2017; Szczepanik et al., 2018; Guan et al., 2019), however, no such detailed studies have been conducted on the comparison of antimicrobial activities of six selected Artemisia species. Hence, the current study encompasses both Gram-positive and Gram-negative bacteria, as well as fungal pathogens to assess the antimicrobial potential of the selected species.

Materials and Methods

Plants collection

The plants and seeds of different species were collected from different localities of Khyber Pakhtunkhwa Province, Pakistan. They were cultivated at Medicinal Botanic Garden, PCSIR, Peshawar. These species namely *Artemisia scoparia*, *Artemisia persica*, *Artemisia arborescens*, *Artemisia absinthium* and *Artemisia vulgaris* were successfully acclimatized at Garden and after reaching to stages of maturity they were collected and identified through taxonomic markers (Fig. 1). Their voucher specimens were prepared and deposited at Herbarium, PCSIR (PES), (Table 1) for future reference.

Table 1 Voucher specimen numbers of Artemisia species at Herbarium, PCSIR, Peshawar (PES)

S. No.	Species	Voucher
1	*Artemisia scoparia*	10696
2	*Artemisia persica*	10697
3	*Artemisia arborescens*	10698
4	*Artemisia absinthium*	10699
5	*Artemisia vulgaris*	10700
6	*Artemisia nilagirica*	10701

PCSIR = Pakistan Council of Scientific and Industrial Research

Extraction

Fresh leaves of six species of Artemisia namely *Artemisia scoparia*, *Artemisia persica*, *Artemisia arborescens*, *Artemisia absinthium*, *Artemisia vulgaris* and *Artemisia nilagirica* were collected and washed with distilled water (Fig. 1). Leaves were dried in shade for 4-5 days and then powdered in blender. The powdered leaves of each species were weighed (Table 2) and extracted with ethanol using rotary evaporator. The extracts were dried under room temperature and the extract yield was measured using following equation:

$$\text{Extract yield} = \left(\frac{\text{Amount of dried extract obtained}}{\text{Total dried weight of powdered aerial parts}}\right) \times 100$$

Subsequently, the dried extracts were dissolved in dimethyl sulfoxide (DMSO) at 100 mg mL^{-1} concentrations and filtered using Millipore syringe filter (0.2 µm pore size). The obtained extracts were stored at 4 °C for detailed analysis.

Tested microorganisms

The strains used in this study were American Type culture and collection (ATCC) strains *viz.*, *Escherichia coli* (ATCC# 8738), *Proteus mirabilis* (ATCC# 12553), *Streptococcus mutans* (ATCC# 35668), *Staphylococcus aureus* (ATCC 6538) and clinical isolates including *Klebsiella pneumonie*, *Salmonella typhi*, *Bacillus subtilis*, *P. aeruginosa* and *Candida albicans* (yeast). The bacterial strains were grown in Nutrient Agar (Merck; Germany) and incubated at 37 °C for 24 h, however, *C. albicans* was grown in potato dextrose agar (PDA) and incubated at 35 °C for 24 h. Azithromycin, Ciprofloxacin, Clotrimazole were used as standard antibiotics for antimicrobial activity.

Table 2 Weight of leaf extracts and the extraction yield obtained from six selected Artemisia species

S. No.	Species	Leaves weight (g)	Extract weight (g)	Extract yield (%)
1	*Artemisia scoparia*	10.48 ± 0.2[a]	2.43 ± 0.04[a]	23.19 ± 2.1[b]
2	*Artemisia persica*	10.19 ± 0.4[a]	2.16 ± 0.03[a]	21.20 ± 1.8[bc]
3	*Artemisia arborescens*	3.76 ± 0.3[c]	1.33 ± 0.05[b]	35.37 ± 2.7[a]
4	*Artemisia absinthium*	10.10 ± 0.2[a]	2.01 ± 0.01[ab]	19.90 ± 0.9[c]
5	*Artemisia vulgaris*	10.10 ± 0.4[a]	1.69 ± 0.02[b]	16.73 ± 1.7[d]
6	*Artemisia nilagirica*	5.90 ± 0.1[b]	1.27 ± 0.02[b]	21.52 ± 2.2[b]

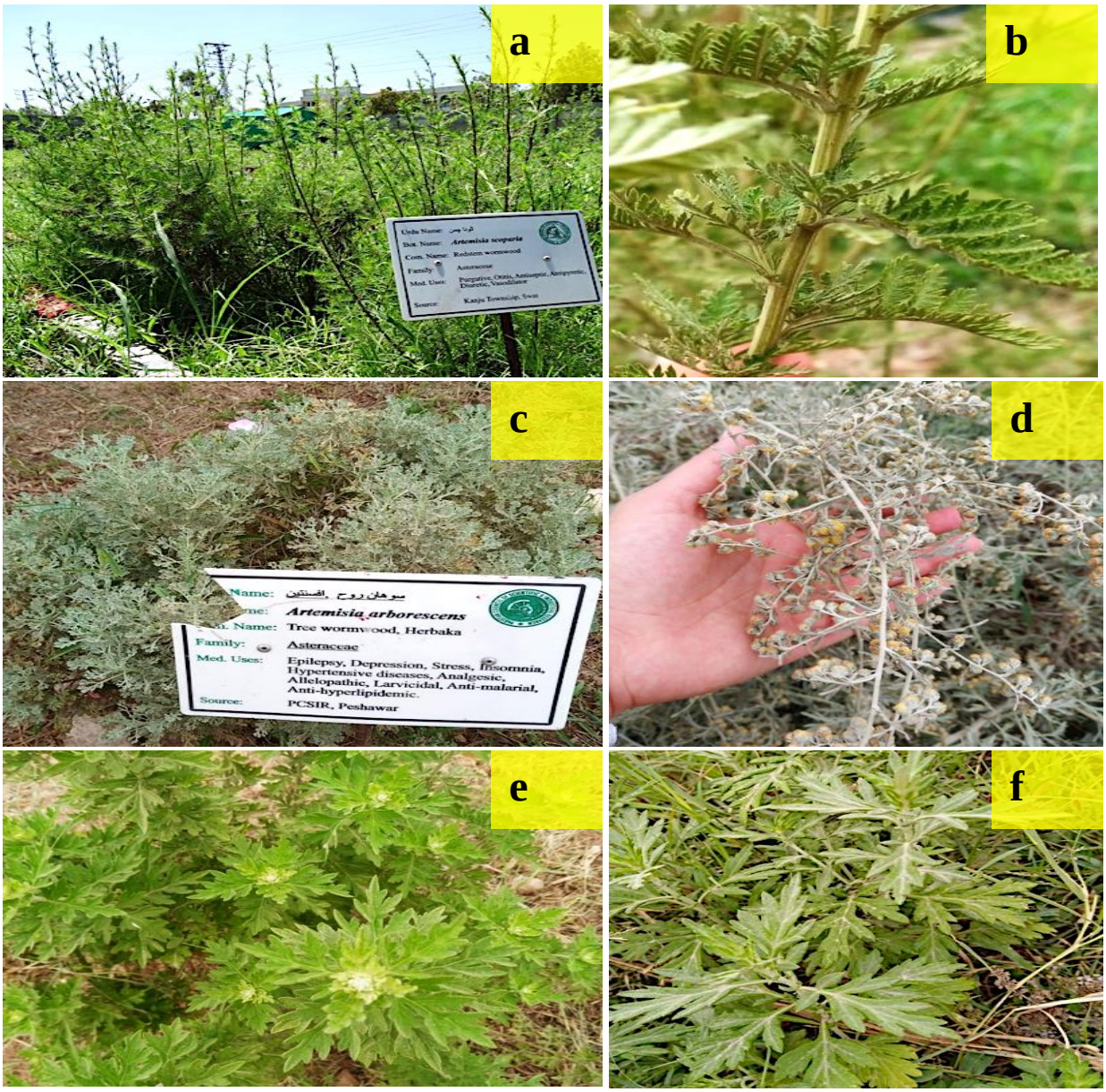

Fig. 1 Pictorial presentation of different species of *Artemisia* (**a**) *Artemisia scoparia* (**b**) *Artemisia persica* (**c**) *Artemisia arborescens* (**d**) *Artemisia absinthium* (**e**) *Artemisia vulgaris* and (**f**) *Artemisia nilagirica*

Antimicrobial assay

Agar well diffusion method was used to evaluate antimicrobial activities of the leaf extracts (Haq et al., 2019). Inocula of the selected bacterial and fungal strains were prepared in normal saline (0.9%) and their turbidity was adjusted with McFarland standard (0.5). 100 µL volume of each microbial strains were swabbed on their respective Muller Hinton agar (MHA) media plates. Wells were punched in MHA and sealed. About 100 µL of volume was taken from each leaf extracts and added in their respective wells. The culture plates were incubated at 37 °C for 24 h and then the antimicrobial activities were observed by measuring the diameter of zone of inhibition (mm). The tests were conducted in duplicate.

Fig. 2 Antimicrobial of *A. scoparia* leaves extracts (100 µL) observed against nine microbial strains **(a)** *E. coli* **(b)** *P. aeruginosa* **(c)** *K. pneumonia* **(d)** *S. typhi* **(e)** *P. mirabilis* **(f)** *S. mutans* **(g)** *S. aureus* **(h)** *B. subtilis* **(i)** *C. albicans.*

Statistical analysis

Three independent experimental replicates (n = 3) were performed for each species to obtain the mean values and standard deviations. Mean values that do not share a common letter are significantly different at $p < 0.05$. Letters in common indicate groups that are not significantly different based on the least significant difference (LSD) test.

Results

Antimicrobial potential of *A. scoparia* leaf extract

The antimicrobial assessment of *A. scoparia* leaf extract revealed measurable inhibitory effects against all tested microbial strains, with inhibition zones ranging from 13.5 mm to 17.5 mm (Fig. 2). The extract produced inhibition zones of 15.5 ± 1.1 mm for E. coli, 17.5 ± 2.3 mm for *P. aeruginosa*, 16.5 ± 0.9 mm for *K. pneumoniae*, 15 ± 1.5 mm for *S. typhi*, 13.5 ± 2.1 mm for *P. mirabilis*, 17 ± 0.9 mm for *S. mutans*, 14.5 ± 1 mm for *S. aureus*, 16 ± 1.1 mm for *B. subtilis*, and 13.5 ± 0.7 mm for *C. albicans*, as presented in Table 3. These findings indicate that the leaf extract exhibits a broad antimicrobial spectrum, with varying degrees of growth inhibition observed across the bacterial and fungal species included in the study.

Antimicrobial potential of *A. persica* leaf extract

The antimicrobial evaluation of *A. persica* leaf extract demonstrated substantial inhibitory activity against all tested microbial strains, with inhibition zones ranging from 15.5 mm to 20.5 mm (Fig. 3; Table 3). The extract produced the largest zones of inhibition against *E. coli* and *B. subtilis*, each measuring 20.5 ± 2.2 mm and 20.5 ± 2.1 mm, respectively. Notable inhibitory effects were also observed for *K. pneumoniae* (19.5 ± 1.3 mm) and *S. mutans* (19.5 ± 1.5 mm), indicating strong responsiveness of these organisms to the extract. Moderate but consistent activity was recorded against *P. aeruginosa* (18.5 ± 1.7 mm), *S. typhi* (18.5 ± 1.3 mm), and *S. aureus* (18 ± 1.9 mm). Lower inhibition values were observed for *P. mirabilis* (15.5 ± 1.8 mm) and *C. albicans* (16.5 ± 0.6 mm), although both strains still exhibited measurable sensitivity to the leaf extract.

Antimicrobial potential of *A. arborescens* leaf extract

The antimicrobial assessment of *A. arborescens* leaf extract revealed a measurable inhibitory effect across all tested microorganisms, with zones of inhibition ranging from 11 mm to 17 mm (Fig. 4). The most prominent activity was observed against *K. pneumoniae*, which exhibited an inhibition zone of 17 ± 1.3 mm, representing the highest response among the evaluated strains. Moderate inhibition was recorded for *B. subtilis* (14 ± 1.2 mm), *S. aureus* (13.5 ± 1.3 mm), and *P. aeruginosa* (13 ± 1.0 mm), indicating consistent susceptibility to the extract. Additionally, inhibition zones of 12.5 ± 0.7 mm, 12.5 ± 1.1 mm, and 12.5 ± 1.1 mm were observed for *E. coli*, *S. typhi*, and *S. mutans*, respectively, reflecting comparatively lower but still notable antimicrobial effects. The least activity was detected against *P. mirabilis* (11.5 ± 1.1 mm) and *C. albicans* (11 ± 0.9 mm), which exhibited the smallest inhibition zones.

Antimicrobial potential of *A. absinthium* leaf extract

The antimicrobial activity of *A. absinthium* leaf extract demonstrated a broad yet variable response across the tested microbial strains, with inhibition zones ranging from 10.5 mm to 15 mm (Fig. 5). The extract showed the strongest activity against *P. aeruginosa*, which produced an inhibition zone of 15 ± 0.9 mm, indicating a relatively high level of sensitivity to the phytochemicals present in the extract. Moderate inhibitory effects were recorded against *K. pneumoniae* (13 ± 0.9 mm), S. aureus (12.5 ± 0.4 mm), and *B. subtilis* (12.5 ± 0.3 mm), suggesting that these organisms exhibit consistent but slightly lower susceptibility. Similarly, inhibition zones of 11.5 ± 0.5 mm and 11.5 ± 0.4 mm were observed for *E. coli* and *S. typhi*, respectively, reflecting modest antimicrobial action. Reduced activity was noted against *P. mirabilis* (12 ± 0.3 mm), while the lowest inhibition zones, both measuring 10.5 mm, were recorded for *S. mutans* (10.5 ± 0.3 mm) and *C. albicans* (10.5 ± 0.4 mm), indicating limited responsiveness to the extract.

Antimicrobial potential of *A. vulgaris* leaf extract

The antimicrobial assessment of *A. vulgaris* leaf extract revealed a variable yet noteworthy inhibitory effect across the tested microbial strains. Overall, the extract produced inhibition zones ranging from 9.5 mm to 15.5 mm (Fig. 6). The strongest response was observed against *S. aureus*, which exhibited an inhibition zone of 15.5 ± 0.4 mm, indicating pronounced sensitivity to the bioactive constituents of the extract. This was followed closely by *B. subtilis* and *P. mirabilis*, both showing inhibition zones of 14.5 ± 0.3 mm and 14.5 ± 0.2 mm, respectively, suggesting that these organisms also respond strongly to the phytochemicals present. Moderate antimicrobial activity was recorded against *C. albicans* (13 ± 0.2 mm), while inhibition zones of 12.5 ± 0.3 mm and 12 ± 0.4 mm were noted for *E. coli* and *P. aeruginosa*, respectively, reflecting a modest but consistent level of sensitivity. Comparatively lower inhibition was observed in *K. pneumoniae* (11 ± 0.2 mm) and *S. mutans* (10.5 ± 0.3 mm), indicating reduced susceptibility. The least responsive strain was *S. typhi*, which produced the smallest inhibition zone of 9.5 ± 0.2 mm. Collectively the results summarized in Table 3 and depicted in Fig. 6 show that *S. aureus*, *B. subtilis*, and *P. mirabilis* are the most sensitive strains to *A. vulgaris*, while *S. typhi* demonstrates comparatively lower sensitivity.

Antimicrobial potential of *A. nilagirica* leaf extract

The antimicrobial evaluation of *A. nilagirica* leaf extract demonstrated a distinct pattern of activity across the tested microbial panel, with inhibition zones ranging from 0.00 mm to 17 mm. The strongest response was recorded against *S. aureus*, which exhibited an inhibition zone of 17 ± 0.9 mm, indicating notable susceptibility to the phytochemical components of the extract. Moderate inhibitory effects were observed against *S. mutans* and *B. subtilis*, each producing zones of 11.5 ± 0.2 mm, while *K. pneumoniae* showed slightly lower sensitivity with a zone of 12.5 ± 0.3 mm. A minimal inhibitory effect was detected in *E. coli* and *P. mirabilis*, both demonstrating inhibition zones of 9.5 ± 0.1 mm and 9.5 ± 0.3 mm, respectively. In contrast, *A. nilagirica* showed complete inactivity against *P. aeruginosa*, *S. typhi*, and *C. albicans*, as evidenced by the absence of any inhibition zones (0.00 mm), suggesting strong resistance or lack of responsiveness in these strains. These findings, summarized in Table 3 and illustrated in Fig. 7, highlight the selective antimicrobial capability of *A. nilagirica*, with particularly strong activity against *S. aureus* and limited or no activity against certain Gram-negative bacteria and fungal species.

Fig. 3 Antimicrobial of *A. persica* leaves extracts (100 µL) observed against nine microbial strains **(a)** *E. coli* **(b)** *P. aeruginosa* **(c)** *K. pneumonia* **(d)** *S. typhi* **(e)** *P. mirabilis* **(f)** *S. mutans* **(g)** *S. aureus* **(h)** *B. subtilis* **(i)** *C. albicans*

Fig. 4 Antimicrobial of *A. arborescens* leaves extracts (100 µL) observed against nine microbial strains **(a)** *E. coli* **(b)** *P. aeruginosa* **(c)** *K. pneumonia* **(d)** *S. typhi* **(e)** *P. mirabilis* **(f)** *S. mutans* **(g)** *S. aureus* **(h)** *B. subtilis* **(i)** *C. albicans*

Fig. 5 Antimicrobial of *A. absinthium* leaves extracts (100 µL) observed against nine microbial strains **(a)** *E. coli* **(b)** *P. aeruginosa* **(c)** *K. pneumonia* **(d)** *S. typhi* **(e)** *P. mirabilis* **(f)** *S. mutans* **(g)** *S. aureus* **(h)** *B. subtilis* **(i)** *C. albicans*

Table 3 Antimicrobial activity observed in six selected Artemisia species against nine microbial strains

Microbial strains	Zone of inhibition (mm)								
	A. scoparia	*A. persica*	*A. arborescens*	*A. absinthium*	*A. vulgaris*	*A. nilagirica*	Azith.	Cipro.	Clot.
E. coli	15.5±1.1	20.5±2.2	12.5±0.7	11.5±0.5	12.5±0.3	9.5±0.1	20±1.1	35±2.6	-
P. aeruginosa	17.5±2.3	18.5±1.7	13±1.0	15±0.9	12±0.4	-	40±2.9	38±3.1	-
K. pneumoniae	16.5±0.9	19.5±1.3	17±1.3	13±0.9	11±0.2	12.5±0.3	23±1.8	-	-
S. typhi	15±1.5	18.5±1.3	12.5±1.1	11.5±0.4	9.5±0.2	-	32±1.9	42±3.2	-
P. mirabilis	13.5±2.1	15.5±1.8	11.5±1.1	12±0.3	14.5±0.2	9.5±0.3	41±2.7	42±2.9	-
S. mutans	17±0.9	19.5±1.5	12.5±1.1	10.5±0.3	10.5±0.3	11.5±0.2	31±2.2	50±3.2	-
S. aureus	14.5±1	18±1.9	13.5±1.3	12.5±0.4	15.5±0.4	17±0.9	38±2.5	35±2.5	-
B. subtilis	16±1.1	20.5±2.1	14±1.2	12.5±0.3	14.5±0.3	11.5±0.2	26±1.6	44±4.1	-
C. albicans	13.5±0.7	16.5±0.6	11±0.9	10.5±0.4	13±0.2	-	-	-	32.5±2.2

Escherichia coli (ATCC# 8738), *Streptococcus mutans* (ATCC# 35668), *S. aureus* (ATCC 6538), *Proteus mirabilis* (ATCC# 12553), *Bacillus subtilis*, *Salmonella typhi*, *Klebsiella pneumonie*, *Candida albicans* (Clinical isolates), *Artemisia scoparia*, Azithromycin (Azithro), Ciprofloxacin (Cipro), Clotrimazole (Clot), $n = 3$ for replicated independent experiment for each species.

Fig. 6 Antimicrobial of *A. vulgaris* leaves extracts (100 µL) observed against nine microbial strains **(a)** *E. coli* **(b)** *P. aeruginosa* **(c)** *K. pneumonia* **(d)** *S. typhi* **(e)** *P. mirabilis* **(f)** *S. mutans* **(g)** *S. aureus* **(h)** *B. subtilis* **(i)** *C. albicans*

Fig. 7 Antimicrobial of *A. nilagirica* leaves extracts (100 µL) observed against nine microbial strains **(a)** *E. coli* **(b)** *P. aeruginosa* **(c)** *K. pneumonia* **(d)** *S. typhi* **(e)** *P. mirabilis* **(f)** *S. mutans* **(g)** *S. aureus* **(h)** *B. subtilis* **(i)** *C. albicans*

Discussion

In current study, antimicrobial potential of six Artemisia species were evaluated using some selected microbial strains. Among all species, *A. persica* showed highest activity as it produced highest inhibition zones against *E. coli*, *B. subtilis*, *K. pneumonia* and *S. mutans*. Our study correlates with the earlier findings of Bidgoli et al. (2021), who observed acceptable antifungal activity in *A. persica* essential oil against *Aspergillus* strains and thus, this specie can be used to prevent food crops from fungal contaminations. Previously, researchers have reported antimicrobial potential in the essential oils of Artemisia species (Bouzenna et al., 2013; Aati et al., 2020). However, present study was designed to evaluate the antimicrobial activity of plant extracts for the first time. Said et al. (2016) collected aerial parts of *Artemisia arborescens* from different sites of the Mediterranean area (Southwestern Algeria and Southern Italy) and determined the antimicrobial activity. Similarly, Bouzenna and Krichen (Bouzenna et al., 2013) determined significant antifungal activity in the essential oil of *A. arborescens* against *Rhizoctonia solani*. The results indicated

that *A. arborescens* may be used as a valuable option in the control of the food-borne pathogens.

Aati et al. (2020) examined antimicrobial activity of the isolated oils of *A.absinthium* and *A. scoparia* growing in Saudi Arabia using broth microdilution method, revealing that the essential oils isolated from the examined *Artemisia* species displayed growth inhibiting actions in a concentration-dependent manner on tested microorganism species. Our study also confirms the previous research findings by Cha et al. (2005); Sengul et al. (2011) who also reported significant antimicrobial potential in *A. scoparia* and *A. absinthum* against the examined strains. Hence, it can be inferred that the examined essential oils could be used to develop effective natural antimicrobial remedies with potential application in the fields of cosmetic industry, food manufacturing and medicine. In present study, *A. nilagirica* exhibited lowest antimicrobial potential and remain inactive against some of the tested strains which can be correlated with the earlier findings of Ahameethunisa and Hopper (2010) who recorded significant inhibitory potential in the methanol and hexane extracts of A. nilagirica against some gram-positive and gram-negative bacteria. Furthermore, Hiremath et al. (2011) determined significant inhibitory activity of the aqueous and alcohol extract of Artemisia vulgaris indicating that the plant can fight these organisms effectively.

Lou et al. (2011) investigated the antibacterial properties and mechanism of action of chlorogenic acid against various pathogenic bacteria. Their findings revealed that chlorogenic acid exhibited strong antibacterial activity, with minimum inhibitory concentration (MIC) values ranging from 20 to 80 µg/mL. The study further demonstrated that chlorogenic acid interacts with and partially disrupts the bacterial outer membrane, resulting in irreversible changes to membrane permeability and a slight leakage of nucleotides. Numerous studies have documented the antimicrobial potential of Artemisia species leaf extracts against a variety of human pathogenic bacteria and fungi (Cosoveanu et al., 2012; Juvatkar et al., 2012; Massiha et al., 2013; Parveen et al., 2014; Tajehmiri et al., 2014; Ghareeb, 2018; Alotibi & Rizwana, 2019; Parameswari et al., 2019; Benderradji et al., 2021). For instance, methanolic leaf extracts of *A. campestris* have demonstrated significant antibacterial activity against several human pathogens (Naili et al., 2010). Similarly, Al-Moghazy et al. (2017) reported that *A. vulgaris* leaf extracts possess antibacterial effects against multiple pathogenic bacterial strains. In contrast, studies examining the antimicrobial efficacy of Artemisia leaf extracts against phytopathogenic fungi and bacteria remain relatively limited (Carvalho et al., 2011; Mengane & Kamble, 2014; Nehad et al., 2017; Ma et al., 2019). Among the few available reports, Mengane and Kamble (2014) as well as Ma et al. (2019) observed that *A. annua* leaf extracts were highly effective against the phytopathogenic fungus *Fusarium oxysporum*. This strong antifungal activity may be linked to the chemical composition of *A. annua* (Potawale et al., 2008; Massiha et al., 2013). In particular, vitexin the second most abundant compound identified in *A. annua* extracts has been suggested to possess important antifungal properties (El-Khateeb, 2010).

Conclusion

The results of this study highlight the significant antimicrobial potential of Artemisia species, indicating that their crude ethanolic extracts may serve as effective natural agents against various diseases caused by resistant microorganisms. Given that plant pathogens are a major constraint to crop productivity worldwide, these findings provide valuable guidelines for future research exploring other Artemisia species as potential sources of bioactive compounds effective against phytopathogens. The promising antimicrobial properties observed in this study suggest that Artemisia-derived extracts can be developed into eco-friendly alternatives to synthetic pesticides and antimicrobial drugs. Nevertheless, further investigations are needed to identify and characterize the specific active compounds responsible for these antimicrobial effects and to better understand their mechanisms of action. Future research should also focus on the endophytic microbial communities inhabiting Artemisia plants and the metabolites they produce, as these symbiotic microorganisms often generate potent bioactive substances that may enhance the antimicrobial efficacy of plant extracts. Combining Artemisia extracts with metabolites from associated endophytes could form the basis for innovative biological control strategies targeting specific phytopathogens. In addition, before practical applications can be recommended, comprehensive toxicological and clinical studies are necessary to evaluate the safety and efficacy of Artemisia-based formulations. Such efforts would support the development of standardized, effective, and safe herbal products that could serve as sustainable alternatives to conventional synthetic antimicrobial agents currently in use.

Declarations

i. Ethics approval and consent to participate

Ethical approval and informed consent were not required for this study as it did not involve human participants, human data, or animals.

ii. Consent for publication

Consent for publication is not applicable.

iii. Data availability

All data generated or analyzed during this study are included in this article.

iv. Competing interests

Authors have declared that no competing interests exist.

v. Authors' contributions

H.F. executed experimental work; I.F. led the conceptualization of the study and guided the overall research design; G.R. managed the development of the methodology and supervised plant growth and stress-tolerance assays; A.H. prepared the initial version of the manuscript; N.A. handled statistical analyses and supported the interpretation of the findings; A.I. refined the manuscript through critical review and revision; M.A. assisted with data validation and ensured the accuracy and consistency of reported results.

vi. Funding

No funding was received for the design, data collection, analysis, interpretation, or writing of this research manuscript.

vii. Acknowledgement

Not applicable.

viii. SDGs addressed

Good Health and Well-Being (SDG 3); Industry, Innovation and Infrastructure (SDG 9); Responsible Consumption and Production (SDG 12)

References

Aati, H. Y., Perveen, S., Orfali, R., Al-Taweel, A. M., Aati, S., Wanner, J., Khan, A., & Mehmood, R. (2020). Chemical composition and antimicrobial activity of the essential oils of *Artemisia absinthium*, *Artemisia scoparia*, and *Artemisia sieberi* grown in Saudi Arabia. *Arabian Journal of Chemistry, 13*(11), 8209–8217.

Abad, M. J., Bedoya, L. M., Apaza, L., & Bermejo, P. (2012). The Artemisia L. genus: A review of bioactive essential oils. *Molecules, 17*(3), 2542–2566. https://doi.org/10.3390/molecules17032542

Ahameethunisa, A. R., & Hopper, W. (2010). Antibacterial activity of *Artemisia nilagirica* leaf extracts against clinical and phytopathogenic bacteria. *BMC Complementary and Alternative Medicine, 10*(1), 1–6.

Al-Moghazy, M., Ammar, M. S., Sief, M. M., & Mohamed, S. R. (2017). Evaluation of the antimicrobial activity of Artemisia and Portulaca plant extracts in beef burger. *Evaluation, 1*(1), 31–42.

Alotibi, F., & Rizwana, H. (2019). Chemical composition, FTIR studies, morphological alterations, and antifungal activity of leaf extracts of *Artemisia sieberi* from Saudi Arabia. *International Journal of Agriculture and Biology, 21*, 1241–1248.

Antimicrobial Resistance Collaborators. (2022). Global burden of bacterial antimicrobial resistance in 2019: A systematic analysis. *The Lancet, 399*(10325), 629–655. https://doi.org/10.1016/S0140-6736(21)02724-0

Behbahani, B. A., Shahidi, F., Yazdi, F. T., Mortazavi, S. A., & Mohebbi, M. (2017). Antioxidant activity and antimicrobial effect of tarragon (*Artemisia dracunculus*) extract and chemical composition of its essential oil. *Journal of Food Measurement and Characterization, 11*, 847–863.

Benderradji, L., Ghadbane, M., Messaoudi, N., & Okki, L. E. E. (2021). *In vitro* multiple solution extracts from leaves of *Artemisia judaica* L. var. *sahariensis* (L. Chevall.) collected from the Algerian Sahara and their antimicrobial activities against pathogenic microorganisms. In M. Ksibi, A. Ghorbal, S. Chakraborty, H. I. Chaminé, M. Barbieri, G. Guerriero, O. Hentati, A. Negm, A. Lehmann, J. Römbke, A. C. Duarte, N. Xoplaki, N. Khélifi, G. Colinet, J. M. Dias, I. Gargouri, E. D. van Hullebusch, B. Sánchez Cabrero, S. Ferlisi, C. Tizaoui, A. Kallel, S. Rtimi, S. Panda, P. Michaud, J. N. Sahu, M. Seffen, & V. Naddeo (Eds.), *Recent Advances in Environmental Science from the Euro-Mediterranean and Surrounding Regions (2nd ed.): Proceedings of the 2nd Euro-Mediterranean Conference for Environmental Integration (EMCEI-2), Tunisia 2019* (pp. 1401–1406). Springer International Publishing.

Berini, F., Orlandi, V., Gornati, R., Bernardini, G., & Marinelli, F. (2022). Nanoantibiotics to fight multidrug-resistant infection by Gram-positive bacteria: Hope or reality? *Biotechnology Advances, 57*, 107948. https://doi.org/10.1016/j.biotechadv.2022.107948

Bidgoli, R. D. (2021). Chemical composition of essential oil and antifungal activity of *Artemisia persica* Boiss. from Iran. *Journal of Food Science and Technology, 58*(4), 1313-1318. https://doi.org/10.1007/s13197-020-04640-x

Blaszyle, M., & Holley, R. A. (1998). Interaction of monolaurin, eugenol, and sodium citrate on growth of common meat spoilage and pathogenic organisms. *International Journal of Food Microbiology, 39*, 175–183.

Bora, K. S., & Sharma, A. (2011). The genus Artemisia: A comprehensive review. *Pharmaceutical Biology, 49*(1), 101–109. https://doi.org/10.3109/13880209.2010.497815

Bouzenna, H., & Krichen, L. (2013). *Pelargonium graveolens* L'Her. and *Artemisia arborescens* L. essential oils: Chemical composition, antifungal activity against *Rhizoctonia solani* and insecticidal activity against *Rhysopertha dominica*. *Natural Product Research, 27*(9), 841–846. https://doi.org/10.1080/14786419.2012.711325

Butler, M. S. (2004). The role of natural product chemistry in drug discovery. *Journal of Natural Products, 67*(12), 2141–2153.

Carvalho, D. D. C., Alves, E., Camargos, R. B., Oliveira, D. F., Scolforo, J. R. S., de Carvalho, D. A., & Batista, T. R. S. (2011). Plant extracts to control *Alternaria alternata* in

Murcott tangor fruits. *Revista Iberoamericana de Micología*, *28*(4), 173–178.

Cha, J. D., Jeong, M. R., Jeong, S. I., Moon, S. E., Kim, J. Y., Kil, B. S., & Song, Y. H. (2005). Chemical composition and antimicrobial activity of the essential oils of *Artemisia scoparia* and *A. capillaris*. *Planta Medica, 71*(2), 186–190.

Cosoveanu, A., Silva, E. D., Gimenez-Marino, C., Núnez Trujillo, G., González-Coloma, A., Frias Viera, I., & Cabrera, R. (2012). Artemisia thuscula Cav.: Antibacterial and antifungal activity of the plant extracts and associated endophytes. *Journal of Horticulture, Forestry, and Biotechnology, 16*(1), 87–90.

Crits-Christoph, A., Hallowell, H. A., Koutouvalis, K., & Suez, J. (2022). Good microbes, bad genes? The dissemination of antimicrobial resistance in the human microbiome. *Gut Microbes, 14*(1), e2055944. https://doi.org/10.1080/19490976.2022.2055944

De Oliveira, D., Forde, B. M., Kidd, T. J., Harris, P., Schembri, M., Beatson, S., Paterson, D., & Walker, M. (2020). Antimicrobial resistance in ESKAPE pathogens. *Clinical Microbiology Reviews*, *33*(3), e00181-19. https://doi.org/10.1128/CMR.00181-19

Dupuis, V., Cerbu, C., Witkowski, L., Potarniche, A. V., Timar, M. C., Zychska, M., & Sabliov, C. M. (2022). Nanodelivery of essential oils as efficient tools against antimicrobial resistance: A review of the type and physicochemical properties of the delivery systems and applications. *Drug Delivery*, *29*(1), 1007–1024. https://doi.org/10.1080/10717544.2022.2056663

Ekiert, H., Świątkowska, J., Klin, P., Rzepiela, A., & Szopa, A. (2021). *Artemisia annua* – Importance in traditional medicine and current state of knowledge on the chemistry, biological activity and possible applications. *Planta Medica, 87*(8), 584–599.

El-Khateeb, H. (2010). Antifungal effect of crude methanolic extract and its fractions of *Jatropha curcas* L. leaves. *Journal of Biological Chemistry*, *5*(3), 671–680.

Fatima, I., Akhtar, W., Bangash, N. K., Kanwal, S., Rauf, N., Malik, T. S., & Mahmood, T. (2022). Volatile profiling, elemental composition and biological activities of aerial parts of seven Poaceae species. *Plant Biosystems*, *156*(4), 908–925.

Ghareeb, H. S. (2018). Antimicrobial activity of Artemisia herba-alba extract against pathogenic fungi of pigeon droppings. *Journal of Plant Protection and Pathology*, *9*(9), 567–571.

Guan, X., Ge, D., Li, S., Huang, K., Liu, J., & Li, F. (2019). Chemical composition and antimicrobial activities of *Artemisia argyi* Lévl. et Vant essential oils extracted by simultaneous distillation-extraction, subcritical extraction and hydrodistillation. *Molecules*, *24*(3), 483. doi: 10.3390/molecules24030483

Haq, A., Siddiqi, M., Batool, S. Z., Islam, A., Khan, A., Khan, D., Khan, S., Khan, H., Shah, A. A., Hasan, F., & Ahmed, S. (2019). Comprehensive investigation on the synergistic antibacterial activities of *Jatropha curcas* pressed cake and seed oil in combination with antibiotics. *AMB Express, 9*(1), 1–21.

Hiremath, S. K., Kolume, D. G., & Muddapur, U. M. (2011). Antimicrobial activity of *Artemisia vulgaris* Linn. (Damanaka). *International Journal of Research in Ayurveda and Pharmacy, 2*(6), 1674–1675.

Ivănescu, B., Burlec, A. F., Crivoi, F., Roșu, C., & Corciovă, A. (2021). Secondary metabolites from Artemisia genus as biopesticides and innovative nano-based application strategies. *Molecules*, *26*(10), 3061. https://doi.org/10.3390/molecules26103061

Juvatkar, P., Jalalpure, S., Waghulde, S., Kale, M., Naik, P., & Jain, V. (2012). Antimicrobial activity of leaves of *Artemisia vulgaris* L. *The 16th International Electronic Conference on Synthetic Organic Chemistry*, Session: Bioorganic, Medicinal, and Natural Products, 1–16.

Keshebo, D. L., Washe, A. P., & Alemu, F. (2016). Determination of antimicrobial and antioxidant activities of extracts from selected medicinal plants. *American Scientific Research Journal for Engineering, Technology, and Sciences*, *16*(1), 212–222.

Khan, Z. U., Khan, N., & Hussain, Z. (2020). Evaluation of secondary metabolites profile and antioxidant potential of *Terminalia chebula* and *Glycyrrhiza glabra*. *Advances in Agriculture and Biology*, *3*(1), 1-7. https://doi.org/10.63072/aab.20001

Liu, N. Q., Van der Kooy, F., & Verpoorte, R. (2009). *Artemisia afra*: A potential flagship for African medicinal plants? *South African Journal of Botany, 75*(2), 185–195.

Lou, Z., Wang, H., Zhu, S., Ma, C., & Wang, Z. (2011). Antibacterial activity and mechanism of action of chlorogenic acid. *Journal of Food Science, 76*, 398–403.

Ma, Y. N., Chen, C. J., Li, Q. Q., Xu, F. R., Cheng, Y. X., & Dong, X. (2019). Monitoring antifungal agents of Artemisia annua against *Fusarium oxysporum* and *Fusarium solani* associated with *Panax notoginseng* root-rot disease. *Molecules*, *24*(1), 213; https://doi.org/10.3390/molecules24010213

Magiorakos, A. P., Srinivasan, A., Carey, R. B., Carmeli, Y., Falagas, M. E., Giske, C. G., Harbarth, S., Hindler, J. F., Kahlmeter, G., Olsson-Lilijequist, B., et al. (2012). Multidrug-resistant, extensively drug-resistant and pandrug-resistant bacteria: An international expert proposal for interim standard definitions for acquired resistance. *Clinical Microbiology and Infection, 18*(3), 268–281. https://doi.org/10.1111/j.1469-0691.2011.03570.x

Massiha, A., Khoshkholgh-Pahlaviani, M. M., Issazadeh, K., Bidarigh, S., & Zarrabi, S. (2013). Antibacterial activity of essential oils and plant extracts of Artemisia (*Artemisia annua* L.) *in vitro*. *Zahedan Journal of Research in Medical Sciences, 15*(6), e92933.

Massiha, A., Khoshkholgh-Pahlaviani, M. M., Issazadeh, K., Bidarigh, S., & Zarrabi, S. (2013). Antibacterial activity

of essential oils and plant extracts of Artemisia (*Artemisia annua* L.) *in vitro*. *Zahedan Journal of Research in Medical Sciences, 15*(6), e92933.

McEwen, S. A., & Collignon, P. J. (2018). Antimicrobial resistance: A one health perspective. *Microbiology Spectrum, 6*(2), ARBA-0009-2017. https://doi.org/10.1128/microbiolspec.ARBA-0009-2017

Mengane, S. K., & Kamble, S. S. (2014). Bioefficacy of plant extracts on *Fusarium oxysporum* f. sp. *cubense* causing Panama wilt of banana. *International Journal of Pharma and Bio Sciences, 4*, 24–27.

Naili, M. B., Alghazeer, R. O., Saleh, N. A., & Al-Najjar, A. Y. (2010). Evaluation of antibacterial and antioxidant activities of *Artemisia campestris* (Asteraceae) and *Ziziphus lotus* (Rhamnaceae). *Arabian Journal of Chemistry, 3*, 79–84.

Nehad, F., Aziz, A., Abdel-Rahman, A. G., Hanan, A., & Hala, A. (2017). Allelopathic activity of some desert plants against plant pathogenic bacteria and nematodes. *Journal of Environmental Science, 37*(2), 15–35.

Nisar, B., Sultan, A., & Rbab, S. L. (2017). Comparison of medicinally important natural products versus synthetic drugs: A short commentary. *Natural Products Chemistry & Research, 6*(1), 1–2.

Owolabi, J., Omogbai, E. K. L., & Obasuyi, O. (2007). Antifungal and antibacterial activities of the ethanolic and aqueous extracts of *Kigelia africana* (Bignoniaceae) stem bark. *African Journal of Biotechnology, 6*(8), 882–885.

Parameswari, P., Devika, R., & Vijayaraghavan, P. (2019). In vitro anti-inflammatory and antimicrobial potential of leaf extract from *Artemisia nilagirica* (Clarke) Pamp. *Saudi Journal of Biological Sciences, 26*(3), 460–463. https://doi.org/10.1016/j.sjbs.2018.09.005

Parameswari, P., Devika, R., & Vijayaraghavan, P. (2019). In vitro anti-inflammatory and antimicrobial potential of leaf extract from *Artemisia nilagirica* (Clarke) Pamp. *Saudi Journal of Biological Sciences, 26*(3), 460–463.

Parveen, S., Wani, A. H., Ganie, A. A., Pala, S. A., & Mir, R. A. (2014). Antifungal activity of some plant extracts on some pathogenic fungi. *Archives of Phytopathology and Plant Protection, 47*(3), 279–284.

Potawale, S. E., Waseem, M., Mehta, U. K., Dhalawat, H. J., Luniya, K. P., & Mantri, R. A. (2008). Research and medicinal potential of *Artemisia annua*: A review. *Pharmacologyonline, 2*, 220–235.

Prestinaci, F., Pezzotti, P., & Pantosti, A. (2015). Antimicrobial resistance: A global multifaceted phenomenon. *Pathogens and Global Health, 109*(7), 309–318. https://doi.org/10.1179/2047773215Y.0000000030

Russo, A., Bruno, M., Avola, R., Cardile, V., & Rigano, D. (2020). Chamazulene-rich *Artemisia arborescens* essential oils affect the cell growth of human melanoma cells. *Plants, 9*(8), 1000. https://doi.org/10.3390/plants9081000

Safir, M. C., Bhavnani, S. M., Slover, C. M., Ambrose, P. G., & Rubino, C. M. (2020). Antibacterial drug development: A new approach is needed for the field to survive and thrive. *Antibiotics, 9*(7), 412. https://doi.org/10.3390/antibiotics9070412

Said, M. E. A., Militello, M., Saia, S., Settanni, L., Aleo, A., Mammina, C., Bombarda, I., Vanloot, P., Roussel, C., & Dupuy, N. (2016). *Artemisia arborescens* essential oil composition, enantiomeric distribution, and antimicrobial activity from different wild populations from the Mediterranean area. *Chemistry & Biodiversity*, *13*(8), 1095–1102.

Sengul, M., Ercisli, S., Yildiz, H., Gungor, N., Kavaz, A., & Çetin, B. (2011). Antioxidant, antimicrobial activity and total phenolic content within the aerial parts of *Artemisia absinthium*, *Artemisia santonicum* and *Saponaria officinalis*. *Iranian Journal of Pharmaceutical Research, 10*(1), 49-56.

Sharifi-Rad, J., Herrera-Bravo, J., Semwal, P., Painuli, S., Badoni, H., Ezzat, S. M., Farid, M. M., Merghany, R. M., Aborehab, N. M., Salem, M. A., & Sen, S. (2022). Artemisia spp.: An update on its chemical composition, pharmacological and toxicological profiles. *Oxidative Medicine and Cellular Longevity, 2022*, 5628601; doi: 10.1155/2022/5628601

Shinyuy, L. M., Loe, G. E., Jansen, O., Mamede, L., Ledoux, A., Noukimi, S. F., Abenwie, S. N., Ghogomu, S. M., Souopgui, J., Robert, A., & Demeyer, K. (2023). Secondary metabolites isolated from *Artemisia afra* and *Artemisia annua* and their anti-malarial, anti-inflammatory and immunomodulating properties—pharmacokinetics and pharmacodynamics: A review. *Metabolites, 13*(5), 613; doi: 10.3390/metabo13050613

Styers, D., Sheehan, D. J., Hogan, P., & Sahm, D. F. (2006). Laboratory-based surveillance of current antimicrobial resistance patterns and trends among Staphylococcus aureus: 2005 status in the United States. *Annals of General Psychiatry, 5*(1), 2. https://doi.org/10.1186/1476-0711-5-2

Subramani, R., Narayanasamy, M., & Feussner, K. D. (2017). Plant-derived antimicrobials to fight against multi-drug-resistant human pathogens. *3 Biotech, 7*(3), 172. https://doi.org/10.1007/s13205-017-0848-9

Szczepanik, M., Walczak, M., Zawitowska, B., Michalska-Sionkowska, M., Szumny, A., Wawrzeńczyk, C., & Brzezińska, M. S. (2018). Chemical composition, antimicrobial activity and insecticidal activity against the lesser mealworm *Alphitobius diaperinus* (Panzer) (Coleoptera: Tenebrionidae) of *Origanum vulgare* L. ssp. hirtum (Link) and *Artemisia dracunculus* L. essential oils. *Journal of the Science of Food and Agriculture, 98*(2), 767–774.

Tajehmiri, A., Issapour, F., Moslem, M. N., Lakeh, M. T., & Kolavani, M. H. (2014). *In vitro* antimicrobial activity of Artemisia annua leaf extracts against pathogenic bacteria. *Advanced Studies in Biology, 6*(3), 93–97.

Ushimaru, P. I., Nogueira da Silva, M. T., Di Stasi, L. C., Barbosa, L., & Fernandes, A. (2007). Antibacterial activity of medicinal plant extracts. *Brazilian Journal of Microbiology, 38*(4), 717–719.

Viegas, C., & Bolzani, V. S. (2006). Produtos naturais e a química medicinal moderna. *Química Nova*, *29*(2), 326–337.

Vieira, T. M., Dias, H. J., Medeiros, T. C., Grundmann, C. O., Groppo, M., Heleno, V. C., Martins, C. H., Cunha, W. R., Crotti, A. E., & Silva, E. O. (2017). Chemical composition and antimicrobial activity of the essential oil of *Artemisia absinthium* (Asteraceae) leaves. *Journal of Essential Oil Bearing Plants*, *20*(1), 123–131.

Vitale, S., Colanero, S., Placidi, M., Di Emidio, G., Tatone, C., Amicarelli, F., & D'Alessandro, A. M. (2022). Phytochemistry and biological activity of medicinal plants in wound healing: An overview of current research. *Molecules*, *27*(11), 3566; doi: 10.3390/molecules27113566

Wu, Z., Chan, B., Low, J., Chu, J. J. H., Hey, H. W. D., & Tay, A. (2022). Microbial resistance to nanotechnologies: An important but understudied consideration using antimicrobial nanotechnologies in orthopaedic implants. *Bioactive Materials*, *16*, 249–270. https://doi.org/10.1016/j.bioactmat.2022.02.014