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Antimicrobial Potential of Omani Medicinal Plants: A Narrative Review

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A B S T R A C T

Objective: Antimicrobial resistance (AMR) is currently one of the most serious threats to human health worldwide. The rapid spread and emergence of multidrug-resistant (MDR) pathogens, including methicillin-, vancomycin-, extended-spectrum β-lactam-, colistin-, and carbapenem-resistant organisms, have made microbial infections difficult to treat. Existing antimicrobials have been widely misused and are becoming largely ineffective, with some also associated with serious side effects. Developing effective, new, and safe antimicrobials is one strategy to reduce the burden of AMR. There is a growing interest in exploring medicinal plants as a source of antimicrobial therapies. Oman has a rich heritage of medicinal plants, and several studies have evaluated their antibacterial activities.

Methods: We reviewed published studies on the antibacterial activity of Omani medicinal plants by searching the PubMed, Google Scholar, Web of Science, and Scopus databases from 2000 to 2006. The studies were systematically compiled to assess the available evidence regarding the antimicrobial properties of these plants.

Results: Studies have reported antibacterial activity of several Omani medicinal plants using preliminary antimicrobial assays, including disc diffusion and liquid dilution assays. None of these studies has provided insight into the antimicrobial mechanism of action of these plants. The compilation of these studies provides an overview of the antimicrobial potential of Omani medicinal plants and their possible role as sources of new antimicrobial agents.

Conclusion: The purpose of this study is to provide insight into the antimicrobial activity of Omani medicinal plants. The findings may help identify plant species with antibacterial activity that warrant further investigation and characterization as potential sources of antibacterial compounds. However, the observed *in vitro* activity does not establish clinical efficacy, safety, or therapeutic potential, and further *in vivo* and clinical studies are required to determine their relevance to addressing AMR.

Keywords: Omani medicinal plants, Antimicrobial activity, Antimicrobial resistance, Phytochemicals

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Introduction

Antimicrobial resistance (AMR) is one of the most important issues facing modern medicine and global public health. According to the 2014 Review on AMR, drug-resistant infections could claim up to 10 million lives annually by the year 2050 [1]. In 2019, approximately 8.9 million deaths were linked to bacterial infections, of which 1.27 million were directly caused by AMR, while 4.95 million were associated with it [2]. The rise of new resistance mechanisms, such as extensively drug-resistant strains and mobile colistin resistance (*mcr*) genes, has made the treatment of microbial infections increasingly challenging [3]. Recent estimates have shown that healthcare costs due to AMR exceed 100 billion USD each year, with forecasts suggesting this figure could reach 300 billion USD by 2030 [4]. These estimates account for direct medical expenses, costlier second-line antibiotic treatments, and prolonged hospital admissions (with resistant infections adding an average of 13 extra days) [5]. Infections acquired in healthcare settings caused by resistant organisms have risen by 35% since 2010, with the most notable increases occurring in long-term care facilities and intensive care units [6]. Weak surveillance systems, insufficient infection control practices, and limited availability of newer antibiotics have made AMR even more challenging in developing countries [7].

The World Health Organisation (WHO) updated its Bacterial Priority List in 2024 to address the growing challenges posed by AMR [8]. In this latest update, the critical priority category was assigned to carbapenem-resistant *Enterobacterales*, carbapenem-resistant *Acinetobacter baumannii*, rifampicin-resistant *Mycobacterium tuberculosis*, and third-generation cephalosporin-resistant *Enterobacterales* [9]. The marked increase in carbapenem-resistant Gram-negative bacteria is of particular concern, given that carbapenems are widely regarded as a last-resort treatment option. The WHO Bacterial Priority Pathogens List classifies these organisms as having low treatability and limited prospects for future therapeutic options [9]. Methicillin-resistant *Staphylococcus aureus* (MRSA) infections also accounted for the largest growth in attributable disease burden over the period from 1990 to 2021 [9]. Most antibiotics in the later phases of development are derivatives of already established drug classes, and resistance has consistently been observed to arise well before the newly developed antibiotics become commercially available [10, 11]. While developing new antibiotics to combat hard-to-treat infections is important, the ongoing emergence of resistance continues to undermine their effectiveness. New strategies are urgently needed to tackle AMR and safeguard the long-term efficacy of antimicrobial treatments.

Medicinal plants have long served as a valuable source of antimicrobial compounds, owing to their rich content of biologically active constituents with therapeutic properties. These naturally derived compounds can exert antimicrobial effects through a variety of mechanisms, including suppression of enzyme activity, disruption of cell membranes, modulation of the immune response, and interference with microbial DNA replication [12]. For instance, the oil derived from the leaves of *Melaleuca alternifolia* (Maiden & Betche) Cheel, also known as tea tree, has broad-spectrum activity against fungi, bacteria, and viruses and is commonly used to treat skin infections [12]. Similarly, curcumin, the main bioactive compound in turmeric, has been found to exhibit antibacterial activity against a broad spectrum of pathogens, including antibiotic-resistant strains [12]. Given that AMR has become a global concern, assessing the potential of plant-derived compounds to combat bacterial infections is critical. These natural compounds offer promising alternatives for the discovery and development of novel antimicrobial agents. This review aims to investigate the antibacterial potential of Omani medicinal plants that are native to or grown in Oman and assess whether the available evidence supports their potential as sources of novel antimicrobial agents that may contribute to addressing the growing challenge of antimicrobial resistance AMR.

Research methodology

A structured literature search was conducted to identify published studies investigating the antimicrobial potential of medicinal plants associated with Oman. PubMed, Google Scholar, Web of Science, and Scopus databases were searched for studies published from 2000 to 2026 using the search terms “antimicrobial” or

"antibacterial" and "Omani medicinal plants" and related combinations. The review included original, peer-reviewed research articles published in English-language scientific journals that investigated the antimicrobial or antibacterial activity of medicinal plants associated with Oman. Studies that did not focus on the antimicrobial or antibacterial properties of Omani medicinal plants, non-peer-reviewed publications, articles published in languages other than English, and duplicate records were excluded. We screened the retrieved records by reviewing titles and abstracts, followed by full-text assessment of potentially eligible articles. Relevant data from the included studies were systematically extracted and compiled to summarise the available evidence on the antibacterial properties of Omani medicinal plants.

Traditional antimicrobial uses of Omani medicinal plants

In Oman, 437 medicinal plant species spanning 283 genera and 95 families have been traditionally used to treat various diseases [13]. Some of these plants are also used to treat antimicrobial infections (Table 1).

Table 1: Traditional uses of Omani medicinal plants as antimicrobial agents

Family	Plant name	Local name	Part used	Traditional uses
Acanthaceae	*Ecbolium viride* (Forssk.) Alston	Alnuwma, Thwaimah	Leave	Leaves used for treating pimples, skin rashes, and earaches
Amaranthaceae	*Celosia argentea* L.	AI-deek	Flower, seeds	Disinfectant and anti-inflammatory
Amaranthaceae	*Seidlitzia rosmarinus* Bunge ex Boiss.	Suad, Aswad, kharizi	Stem and leaves	Applied for dizziness, gum infections and nausea
Amaranthaceae	*Suaeda aegyptiaca* (Hasselq.) Zohary	Maliah	Stem and leaves	Gum and tooth infections and improving poor vision
Apiaceae	*Ammi majus* L.	AI khutat, Arnage aoun, Nainha	Fruits	Dried fruits are used for infections of the urinary tract and the treatment of skin disorders

Apocynaceae	*Calotropis procera* (Aiton) W.T.Aiton	Ashakhar	Leaves, latex, roots	The bark roots to treat dysentery, the latex is used for skin ailments, the leaf powder is used for worm infections, and dried leaves are smoked for asthma
Apocynaceae	*Caralluma flava* N.E.Br.	Dur al Kebeh	Whole plant	Aerial parts are used as a tonic and for stomach ailments
Apocynaceae	*Nerium oleander* L.	Haban	Leaves, roots	Roots and leaves are used for itching, skin diseases, tumours, and ulcers. Leaves are used to cure bronchitis and sinusitis
	Sarcostemma viminale (L.) R.Br.	Beedowl	Latex	Wounds, burns, skin infection
Aristolochiaceae	*Aristolochia bracteolata* Lam.	Ghagha, Mekhisa	Whole plant	Used to treat scorpion and snake bites and for skin problems
Asteraceae	*Tagetes erecta* L.	Almakhmaliat	Leaves	Antiseptic
Boraginaceae	*Cordia myxa* L.	Bamiraah, Kao, dabag, makhet	Seeds	Seeds are eaten to cure diarrhea
	Heliotropium longiflorum Phil.	Hablim, Shebram	Leaves	For eye and skin infection
Cyperaceae	*Cyperus rotundus* L.	Saad asir	Seeds	Seeds are used as a diuretic, and used to treat

				aching gums and teeth problems
Euphorbiaceae	*Euphorbia larica* Boiss.	Isbuq	Latex	The latex is used to treat skin problems and earache
Lamiaceae	*Ocimum forskaolii* Benth.	Rehan	Leaves, seeds	Seeds boiled in water and taken as a drink for diarrhea, leaves for cold, diarrhea
	Salvia aegyptiaca L.	Rael, Berahoo, maru	Seeds	The seeds are used for diarrhea and piles
Malvaceae	*Abutilon pannosum* (G.Forst.) Schltdl.	Qarqa	Leaves	The leaves are used for diarrhea
Molluginaceae	*Glinus lotoides* L.	Hambaz	Whole plant	Used for diarrhea and pain in limbs
Oleaceae	*Jasminum grandiflorum* L.	Yasmeen	Leaves, flower	Dried flowers and leaves for dysentery, abdominal pain and leaves used as a purgative
Orobanchaceae	*Cistanche tubulosa* (Schenk) Wight ex Hook.f.	Dhunun `anbubi	Leaf, flowers	Diarrhea and jaundice
Plantaginaceae	*Plantago major* L.	Waraq	Seeds	Seeds are used in dysentery, diarrhea, and to treat fever

Plumbaginaceae	*Limonium axillare* (Forssk.) Kuntze	Alqatf, Khazamaa albahr	Whole plant	Whole plant is used for diarrhea and as an astringent
Primulaceae	*Anagallis arvensis* L.	Eawaynat, Eayan, alqatwat	Whole plant	Used against blisters, skin rashes, and skin ulcers

Antimicrobial mechanism of action

Antimicrobial compounds may be classified into six main categories according to their modes of action. These mechanisms include alteration of plasma membrane integrity, suppression of cell wall synthesis, impairment of nucleic acid synthesis, disruption of cellular energy production, modification of essential metabolic pathways, and interference with protein synthesis (Fig. 1) [14].

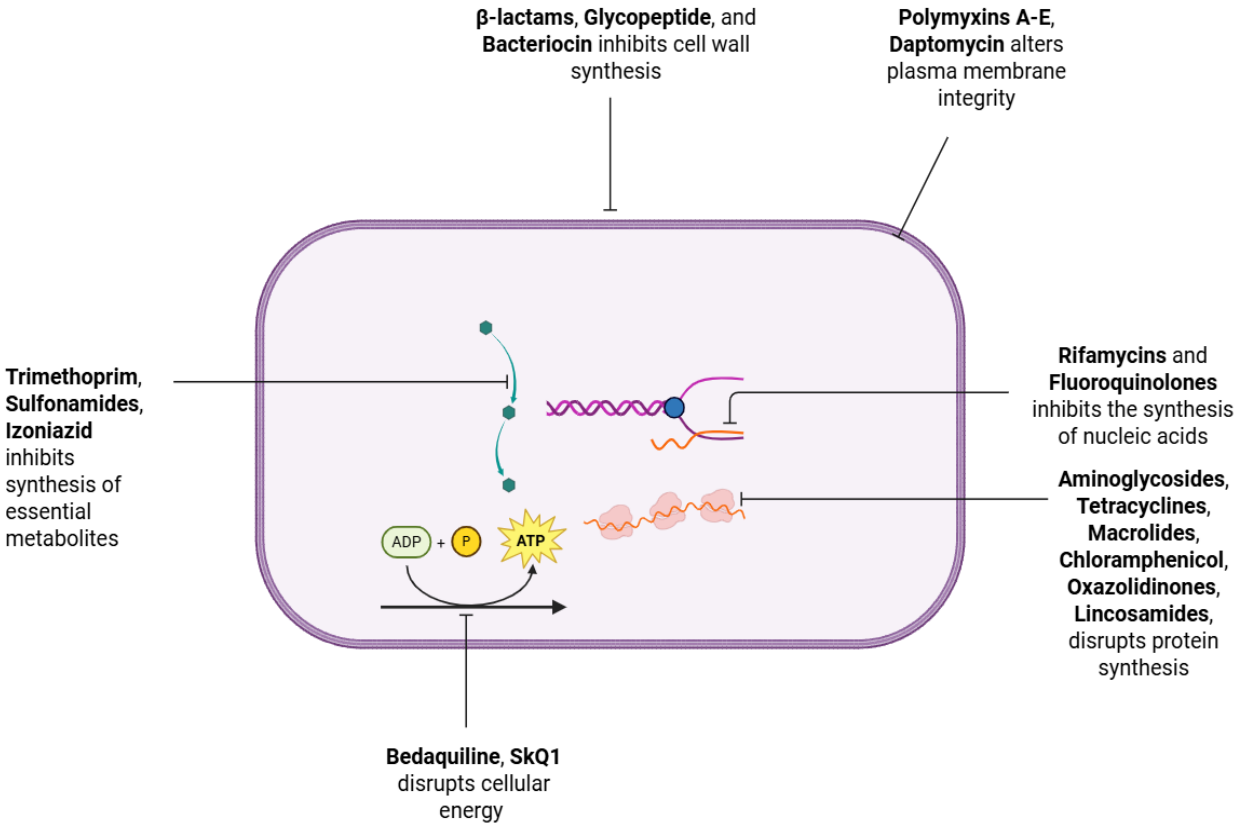


Fig. 1 Antimicrobial drug mechanisms of action included inhibition of cell wall synthesis, synthesis of essential metabolites, synthesis of nucleic acids, disruption of protein synthesis and alteration of plasma membrane integrity

The cell wall is essential for maintaining the structural rigidity of bacterial cells. Glycopeptides, β-lactams, and bacitracin are among the classes of antibiotics that work by interfering with the biosynthesis of components of the bacterial cell wall [15]. The glycopeptide antibiotic vancomycin binds to the D-alanine-D-alanine motif of peptidoglycan precursors, disrupting the formation of cell walls. Furthermore, it also inhibits the activity of enzymes that catalyse important

biochemical processes related to cell wall stability, such as transpeptidases and D-D-carboxypeptidases [15]. The main structural element of the bacterial cell wall, peptidoglycan strands, are cross-linked by the transpeptidase enzyme, which is inhibited by penicillin, an antibiotic with a β-lactam ring [16]. Bacitracin disrupts the transport of peptidoglycan precursor units to the cell membrane through inactivation of the phospholipid carrier [17].

The cell membrane functions as a selective barrier, allowing the controlled transport of necessary molecules while blocking the uncontrolled movement of water, nutrients, and ions [18]. Both Gram-positive and Gram-negative bacteria can be effectively inhibited by antibacterial agents that target the cytoplasmic membrane [19]. For instance, polymyxins A-E increase cellular permeability and destabilise the phospholipid structure of membranes. Gram-negative bacteria are especially vulnerable to these antibiotics due to their higher phospholipid content in both the cytoplasmic and outer membranes [19]. All cells, including bacterial cells, rely on the production of energy through interrelated metabolic processes. Energy, whether in the form of ATP or membrane potential, is necessary for several cellular processes. Bedaquiline inhibits the production of ATP by blocking the membrane-bound F1Fo-ATP synthase [20]. SkQ1 causes protonophore-like futile cycles, which interfere with the generation of membrane potential [21].

Antibiotics that inhibit and target nucleic acid synthesis are frequently used in clinical practice. Their ability to disrupt the essential mechanisms of bacterial transcription and replication accounts for their efficacy against a variety of microbial infections. These antibiotics fall into two main categories: those that work as nucleotide analogues by joining polynucleotide chains during RNA or DNA synthesis and those that hinder RNA and DNA synthesis by blocking the enzymes involved in these processes [22, 23]. For example, rifamycins such as rifabutin, rifampin, and rifapentine work by inhibiting the activity of bacterial RNA polymerase [24]. Fluoroquinolones such as levofloxacin, ciprofloxacin, and moxifloxacin inhibit the activity of DNA gyrase and topoisomerase IV [25, 26].

Tetracyclines, aminoglycosides, chloramphenicol, and macrolides are members of a different class of antibiotics that work by preventing the synthesis of bacterial proteins. Tetracyclines target the bacterial ribosome's 30S subunit and prevent aminoacyl-tRNA from binding to the A-site, which stops protein elongation and stops new amino acids from being added to the expanding peptide chain [27]. Gentamicin, streptomycin, and tobramycin are examples of aminoglycosides that bind to the 30S subunit of the bacterial ribosome. This causes the mRNA to be misread during translation, which leads to the incorrect amino acids being incorporated into the polypeptide chain [28]. Macrolides such as azithromycin, erythromycin, and clarithromycin bind to the bacterial ribosome's 50S subunit and prevent peptidyl-tRNA from moving from the ribosome's A-site to its P-site [29]. When used together to treat microbial infections, sulphonamides and trimethoprim, which are members of two different antibiotic classes, frequently exhibit synergistic effects. By focusing on different stages of this biosynthesis pathway, both antibiotics interfere with the synthesis of tetrahydrofolate, a crucial substance needed for the synthesis of nucleotides [30]. Trimethoprim blocks dihydrofolate reductase, the enzyme responsible for a key step in tetrahydrofolate synthesis, while sulphonamides act as a competitive inhibitor of dihydropteroate synthase [31, 32].

Antimicrobial activity of Omani medicinal plant extracts

Several studies have recorded the antibacterial activity of Omani medicinal plant extracts against a range of pathogens (Table 2). Most of these investigations were conducted using *in vitro* models and preliminary antimicrobial screening methods, including disc diffusion and broth microdilution assays. The ZOI values are influenced by several methodological factors, including the concentration of the tested sample, solvent used, diffusion characteristics of the test compounds, agar composition and thickness, inoculum density, volume applied to the disc, and incubation conditions. Therefore, ZOI values obtained under different experimental conditions should not be directly compared across studies. However, none of these studies has provided mechanistic insights into the antimicrobial modes of action of these

plants. The strength of the available evidence varies substantially among studies, with much of the evidence derived from *in vitro* assays, while animal and clinical evidence remains limited; therefore, reported antibacterial activity should be interpreted in the context of the study design and its methodological limitations.

Table 2: Antimicrobial activity of Omani medicinal plant extracts

Plant name	Parts used	Solvent	Antimicrobial activity against	Minimum inhibitory concentration (MIC) (mg/ml)	Zone of inhibition (ZOI) (mm)	References
Ocimum basilicum L.	Leaves and stems	Ethanol	*Bacillus subtilis*	6.47	15 ± 0.3	[33]
			Staphylococcus aureus	1.28	21 ± 0.2	
			Micrococcus luteus	2.87	19 ± 0.2	
			Salmonella enteritidis	1.28	15 ± 0.3	
			Escherichia coli	1.34	20 ± 0.2	
			Klebsiella pneumonia	9.26	08 ± 0.01	
Teucrium polium L.		Ethanol	*Bacillus cereus*	3.45	18 ± 0.5	
			B. subtilis	1.47	20 ± 0.2	
			M. luteus	8.74	11 ± 0.3	
			S. enteritidis	9.15	09 ± 0.1	
			E. coli	2.69	18 ± 0.3	

			K. pneumonia	1.37	15 ± 0.2	
Caralluma arabica N.E.Br		Ethanol	*B. subtilis*	9.41	11 ± 0.5	
			S. aureus	1.68	22 ± 0.1	
			S. enteritidis	9.87	10 ± 0.33	
			K. pneumonia	3.37	12 ± 0.0	
Cleome amblyocarpa Barratte & Murb.		Ethanol	*B. subtilis*	9.39	11 ± 0.5	
			M. luteus	1.71	21 ± 0.1	
			S. enteritidis	8.78	07 ± 0.4	
			E. coli	8.73	12 ± 0.1	
			K. pneumonia	8.83	07 ± 0.0	
Commiphora gileadensis (L.) C.Chr	Leaves and seeds	Methanol	*S. aureus*	0.00625 (leaves) 0.00156 (seeds)	25 ± 0.7 (leaves) 23 ± 1.7 (seeds)	[34]
			Staphylococcus epidermis	0.00312 (leaves)	15 ± 0.9 (leaves)	

			Salmonella spp.	0.0125 (leaves)	17 ± 1.4 (leaves)	
Ziziphus jujuba Mill.	Leaves and fruits	Hexane	*E. coli*	-	17 ± 0.10 (leaves) 10 ± 0.15 (fruit)	[35]
			Proteus spp	-	10 ± 0.12 (leaves) 14 ± 0.10 (fruit)	
			S. aureus	-	14 ± 0.23 (leaves) 10 ± 0.12 (fruit)	
			Haemophilus influenza	-	13 ± 0.32 (leaves) 12 ± 0.12 (fruit)	
		Ethyl acetate	*E. coli*	-	14 ± 0.19 (leaves) 15 ± 0.10 (fruit)	
			Proteus spp	-	15 ± 0.10 (leaves) 14 ± 0.16 (fruit)	
			S. aureus	-	10 ± 0.20 (leaves) 14 ± 0.10 (fruit)	
			H. influenza	-	13 ± 0.31 (leaves) 13 ± 0.18 (fruit)	

		Chloroform	*E. coli*	-	12 ± 0.11 (leaves) 13 ± 0.23 (fruit)	
			Proteus spp.	-	14 ± 0.34 (leaves) 14 ± 0.19 (fruit)	
			S. aureus	-	12 ± 0.13 (leaves) 14 ± 0.10 (fruit)	
			H. influenza	-	16 ± 0.71 (leaves) 13 ± 0.14 (fruit)	
		Butanol	*E. coli*	-	9 ± 0.19 (leaves) 14 ± 0.19 (fruit)	
			Proteus spp.	-	14 ± 0.28 (leaves) 13 ± 0.17 (fruit)	
			S. aureus	-	16 ± 0.43 (leaves) 13 ± 0.12 (fruit)	
			H. influenza	-	9 ± 0.12 (leaves) 12 ± 0.19 (fruit)	
		Methanol	*E. coli*	-	14 ± 0.10 (leaves) 13 ± 0.10 (fruit)	

			Proteus spp.	-	10 ± 0.12 (leaves) 16 ± 0.10 (fruit)	
			S. aureus	-	12 ± 0.09 (leaves) 12 ± 0.11 (fruit)	
			H. influenza	-	13 ± 0.10 (leaves) 10 ± 0.18 (fruit)	
		Water	*E. coli*	-	11 ± 0.15 (leaves) 15 ± 0.27 (fruit)	
			Proteus spp.	-	10 ± 0.12 (leaves) 14 ± 0.17 (fruit)	
			S. aureus	-	14 ± 0.20 (leaves) 12 ± 0.49 (fruit)	
			H. influenza	-	7 ± 0.15 (leaves) 12 ± 0.17 (fruit)	
Datura metel L.	Leaves	Hexane	*E. coli*	-	9 ± 0.15	[36]
			Pseudomonas aeruginosa	-	9 ± 0.17	

		Chloroform	*E. coli*	-	13 ± 0.43	
		Ethyl acetate	*E. coli*	-	7 ± 0.22	
			S. aureus	-	8 ± 0.90	
			P. aeruginosa	-	7 ± 0.19	
		Butanol	*E. coli*	-	9 ± 0.13	
			S. aureus	-	9 ± 0.20	
		Methanol	*E. coli*	-	8 ± 0.18	
			S. aureus	-	7 ± 0.38	
Ficus sycomorus L.	Fruits	Hexane	*E. coli*	-	7 ± 0.18	[37]
			S. aureus	-	7 ± 0.13	
		Chloroform	*E. coli*	-	8 ± 0.21	
			Proteus spp.	-	9 ± 0.23	

			S. aureus	-	7 ± 0.51	
		Ethyl acetate	*E. coli*	-	7 ± 0.14	
			Proteus spp.		11 ± 0.19	
			S. aureus		10 ± 0.23	
		Butanol	*E. coli*	-	8 ± 0.35	
			Proteus spp.	-	12 ± 0.15	
			S. aureus		10 ± 0.55	
			H. influenza		15 ± 0.14	
		Methanol	*E. coli*	-	9 ± 0.18	
			Proteus spp.		10 ± 0.24	
			S. aureus		6 ± 0.12	
		Water	*E. coli*	-	11 ± 0.13	

			Proteus spp.		14 ± 0.17	
			S. aureus		11 ± 0.10	
Ammi majus L.	Seeds	Methanol	*S. aureus*		8 ± 0.17	[38]
			E. coli	-	11 ± 0.10	
			Proteus spp.		9 ± 0.16	
		Hexane	*H. influenza*	-	8 ± 0.41	
			S. aureus	-	11 ± 0.13	
			E. coli	-	10 ± 0.08	
			Proteus spp.	-	9 ± 0.17	
		Chloroform	*H. influenza*	-	9 ± 0.16	
			S. aureus	-	9 ± 0.20	
			E. coli	-	12 ± 0.10	
			Proteus spp.	-	8 ± 0.18	

		Ethyl acetate	*H. influenza*	-	7 ± 0.09	
			S. aureus	-	8 ± 0.17	
			E. coli	-	10 ± 0.42	
		Butanol	*H. influenza*	-	8 ± 0.43	
			S. aureus	-	9 ± 0.15	
			E. coli	-	7 ± 0.23	
			Proteus spp.	-	9 ± 0.18	
		Water	*H. influenza*	-	9 ± 0.10	
			S. aureus	-	7 ± 0.44	
			E. coli	-	9 ± 0.10	
			Proteus spp.	-	8 ± 0.15	
Terminalia dhofarica (A.J.Scott) Gere & Boatwr.	Leaves	Methanol	*Aliivibrio fischeri*	0.5	-	[39]

Boswellia sacra Flueck.	Oleoresin	Methanol	*E. coli*	1.16	-	[40]
			Enterococcus faecalis	0.47	-	
			S. aureus	0.62	-	
			Salmonella newport	0.14	-	
			S. sonnei	1.34	-	
			Proteus mirabilis	0.60	-	
			K. pneumoniae	0.62	-	
			Acinetobacter baylyi	0.80	-	
		Water	*E. coli*	2.7	-	
			E. faecalis	1.86	-	
			S. aureus	1.87	-	
			S. newport	1.24	-	
			P. mirabilis	1.55	-	
			K. pneumoniae	2.25	-	

			A. baylyi	1.87	-	
Lawsonia inermis Linn	Seeds and leaves combined	Ethanol	*S. epidermis*	-	25	[41]
			S. aureus	-	21	
			E. coli	-	13	
			P. aeruginosa	-	18	
			Bacillus spp.	-	25	
			K. pneumoniae	-	14	
			Salmonella spp.	-	13	
			Shigella sonnei	-	15	
			Citrobacter freundii	-	17	
			Vibrio cholerae	-	30	
			Neisseria meningitidis	-	25	
			H. influenzae	-	22	
			Aeromonas hydrophila	-	25	

			Methicillin-resistant *Staphylococcus aureus*	-	30	
			Micrococcus spp.	-	25	
			Corynebacterium diphtheriae	-	15	
			Streptococcus pyogenes	-	25	
			Streptococcus pneumoniae	-	21	
			Bacteroides fragilis	-	20	
			Clostridium perfringens	-	30	
Omani *Gum acacia*	Latex	Hexane	*K. pneumoniae*	-	8 ± 0.09	[42]
			E. coli	-	10 ± 0.07	
			S. aureus	-	8 ± 0.32	
		Chloroform	*K. pneumoniae*	-	11 ± 0.14	
			E. coli	-	9 ± 0.22	
			S. aureus	-	10 ± 0.09	

		Ethyl acetate	*K. pneumoniae*	-	9 ± 0.07	
			E. coli	-	9 ± 0.98	
			S. aureus	-	9 ± 0.23	
		Butanol	*K. pneumoniae*	-	10 ± 0.14	
			E. coli	-	10 ± 0.17	
			S. aureus	-	10 ± 0.09	
		Water	*K. pneumoniae*	-	10 ± 0.10	
			E. coli	-	11 ± 0.67	
			S. aureus	-	9 ± 0.17	
Ajuga iva (L.) Scherb.	Leaves, stems, roots	Ethanol	*E. coli*	-	13.3	[43]
			S. aureus	-	18.3	
			B. subtilis	-	18.3	
		Ethanol	*E. coli*	-	18.6	

Pteropyrum scoparium Jaub. & Spach			*S. aureus*	-	21	
			B. subtilis	-	18.6	
Rhazya stricta Decne.		Ethanol	*E. coli*	-	13.3	
			S. aureus	-	21.6	
			B. subtilis	-	19.6	
Mentha piperita L.	Leaves	Hexane	*E. coli*	-	9 ± 0.12	[44]
			S. aureus		12 ± 0.49	
			Xanthomonas campestris		11 ± 0.23	
		Ethyl acetate	*E. coli*	-	6 ± 0.31	
			S. aureus	-	8 ± 0.62	
			X. campestris	-	8 ± 0.64	
		Chloroform	*E. coli*	-	10 ± 0.11	
			S. aureus	-	10 ± 0.44	
			X. campestris	-	11 ± 0.16	
		Butanol	*E. coli*	-	6 ± 0.20	

			S. aureus	-	12 ± 0.19	
			X. campestris	-	-	
		Essential oil	*E. coli*	-	14 ± 0.27	
			S. aureus	-	10 ± 0.10	
			X. campestris	-	9 ± 0.15	
Citrus aurantifolia L.	Leaves	Essential oil	*E. coli*	-	3.1 ± 0.6	[45]
			S. aureus	-	7.9 ± 1.2	
Rhus aucheri Boiss	Leaves	30% aqueous glycerol	*E. faecalis*	-	40 ± 1.0	[46]
		Water	*S. aureus*	-	11.7 ± 1.5	
Adenium obesum (Forssk.) Roem. & Schult	Leaves	Hexane	*E. coli*	-	12 ± 0.12	[47]
			P. aeruginosa	-	11 ± 0.09	
			S. aureus	-	11 ± 0.10	
			Proteus vulgaris	-	10 ± 0.18	
		Ethyl acetate	*E. coli*	-	9 ± 0.10	
			P. aeruginosa	-	10 ± 0.12	

			S. aureus	-	-	
			P. vulgaris	-	10 ± 0.10	
		Chloroform	*E. coli*	-	9 ± 0.16	
			P. aeruginosa	-	10 ± 0.10	
			S. aureus	-	12 ± 0.11	
			P. vulgaris	-	10 ± 0.10	
		Butanol	*E. coli*	-	9 ± 0.19	
			P. aeruginosa	-	7 ± 0.16	
			S. aureus	-	11 ± 0.13	
			P. vulgaris	-	10 ± 0.32	
		Methanol	*E. coli*	-	8 ± 0.23	
			P. aeruginosa	-	-	
			S. aureus	-	-	
			P. vulgaris	-	9 ± 0.26	
		Water	*E. coli*	-	10 ± 0.43	
			P. aeruginosa	-	7 ± 0.10	

			S. aureus	-	9 ± 0.77	
			P. vulgaris	-	9 ± 0.47	
Juniperus excelsa M.Bieb.	Leaves	Hexane	*E. coli*	-	-	[48]
			S. aureus	-	13 ± 0.11	
			P. aeruginosa	-	8 ± 0.32	
		Chloroform	*E. coli*	-	8 ± 0.15	
			S. aureus	-	8 ± 0.22	
			P. aeruginosa	-	10 ± 0.14	
		Ethyl acetate	*E. coli*	-	7 ± 0.41	
			S. aureus	-	11 ± 0.14	
			P. aeruginosa	-	10 ± 0.17	
		Hydroalcoholic	*E. coli*	-	-	
			S. aureus	-	9 ± 0.32	
			P. aeruginosa	-	7 ± 0.21	
Cymbopogon schoenanthus (L.) Spreng	Not reported	Methanol	*E. coli*	-	2.5 ± 0.5	[49]
			Klebsiella	-	2.75 ± 0.9	

			Staphylococcus	-	5 ± 2.6	
			Bacillus	-	3 ± 0.8	
Laurus nobilis L.	Leaves	Essential oil	*E. coli*	-	6 ± 0.21	[50]
			S. aureus	-	14 ± 0.09	
			P. aeruginosa	-	12 ± 0.55	
			Candida albicans	-	7 ± 0.17	
Boswellia sacra Flueck.	Oleogum resin	Essential oil (Najdi)	*S. aureus*	210	-	[51]
			P. aeruginosa	>210	-	
			S. epidermis	52	-	
			Staphylococcus hominis	210	-	
			Propionibacterium acne	>210	-	
		Essential oil (Sahli)	*S. aureus*	210	-	
			P. aeruginosa	210	-	
			S. epidermis	5.88	-	
			S. hominis	210	-	
			P. acne	210	-	

		Essential oil (Houjri)	*S. aureus*	200	-	
			P. aeruginosa	>200	-	
			S. epidermis	400	-	
			S. hominis	>200	-	
			P. acne	>200	-	
Teucrium stocksianum Boiss.	Leaves	Essential oil	*S. aureus*	4.5	16	[52]
			Streptomyces albus	5.5	17	
			S. epidermis	5	16.5	
			Streptococcus mitis	5	18.5	
			Streptococcus sanguis	4.5	17	
			M. luteus	5.5	9	
			B. subtilis	5	16.5	
			B. cereus	4.5	17.5	
			E. coli	8.5	14	
			Enterobacter aerogenes	8	8	
			K. pneumoniae	7.5	9	

			Salmonella typhi	6.5	13	
			P. vulgaris	-	7.5	
			P. aeruginosa	10	11	
Rubus fruticosus L.	Leaves	Methanol	*E. coli*	-	10 ± 0.24	[53]
			H. influenza	-	10 ± 0.71	
			E. faecalis	-	10 ± 0.11	
			S. aureus	-	-	
		Hexane	*E. coli*	-	9 ± 0.31	
			H. influenza	-	6 ± 0.19	
			E. faecalis	-	9 ± 0.27	
			S. aureus	-	6 ± 0.72	
		Chloroform	*E. coli*	-	14 ± 0.11	
			H. influenza	-	6 ± 0.18	
			E. faecalis	-	10 ± 0.09	
			S. aureus	-	-	
		Ethyl acetate	*E. coli*	-	21 ± 0.71	

			H. influenza	-	8 ± 0.45	
			E. faecalis	-	9 ± 0.32	
			S. aureus	-	-	
		Hydro alcoholic	*E. coli*	-	9 ± 0.15	
			H. influenza	-	8 ± 0.18	
			E. faecalis	-	10 ± 0.88	
			S. aureus	-	6 ± 0.42	
Coleus aromaticus Benth.	Leaves	Hydro alcoholic	*S. aureus*	-	7	[54]
		Ethyl acetate	*S. aureus*	-	11	
		Chloroform	*E. coli*	-	7	
Tetraena simplex (L.) Beier & Thulin	Aerial parts	Hexane	*S. aureus*	-	9 ± 0.10	[55]
		Methanol	*S. aureus*	-	10 ± 0.37	
		Ethyl acetate	*K. pneumoniae*	-	10 ± 0.21	
			Paenibacillus	-	6 ± 0.14	
			S. pneumoniae	-	10 ± 0.27	

Boswellia sacra Flueck.	Commercial frankincense	Essential oil (Shabi)	*S. aureus*	62.5	-	[56]
			E. coli	15.6	-	
			P. aeruginosa	62.5	-	
			Bacillus spp.	62.5	-	
			Candida albicans	31.3	-	
			Saccharomyces cerevisiae	15.6	-	
			Aspergillus flavous	125	-	
			Aspergillus ochraceus	125	-	
			Aspergillus niger	62.5	-	
			Penicillium citrinum	125	-	
			Alternaria alternata	62.5	-	
			Fusarium solani	15.6	-	
		Essential oil (Hojari)	*S. aureus*	62.5	-	
			E. coli	15.6	-	
			P. aeruginosa	62.5	-	

			Bacillus spp.	62.5	-	
			C. albicans	62.5	-	
			S. cerevisiae	31.3	-	
			A. flavous	125	-	
			A. ochraceus	125	-	
			A. niger	62.5	-	
			P. citrinum	125	-	
			A. alternata	62.5	-	
			F. solani	15.6	-	
Piper nigrum L.	Aerial parts	Methanol	*S. saprophyticus*	-	10 ± 0.21	[57]
			S. aureus	-	12 ± 0.09	
			P. vulgaris	-	12 ± 0.19	
			Kurthia senegalensis	-	9 ± 0.15	
			E. coli	-	13 ± 0.18	
		Hexane	*S. saprophyticus*	-	11 ± 0.13	
			S. aureus	-	10 ± 0.14	

			P. vulgaris	-	14 ± 0.12	
			K. senegalensis	-	12 ± 0.44	
			E. coli	-	15 ± 0.18	
		Chloroform	*S. saprophyticus*	-	11 ± 0.55	
			S. aureus	-	10 ± 0.16	
			P. vulgaris	-	11 ± 0.09	
			K. senegalensis	-	10 ± 0.24	
			E. coli	-	12 ± 0.21	
		Ethyl acetate	*S. saprophyticus*	-	12 ± 0.09	
			S. aureus	-	15 ± 0.16	
			P. vulgaris	-	10 ± 0.25	
			K. senegalensis	-	10 ± 0.09	
			E. coli	-	11 ± 0.90	
		Butanol	*S. saprophyticus*	-	11 ± 0.11	
			S. aureus	-	8 ± 0.51	
			P. vulgaris	-	9 ± 0.79	

			K. senegalensis	-	10 ± 0.10	
			E. coli	-	11.5 ± 0.56	
		Water	*S. saprophyticus*	-	10 ± 0.34	
			S. aureus	-	9 ± 0.77	
			P. vulgaris	-	10 ± 0.14	
			K. senegalensis	-	10 ± 0.18	
			E. coli	-	10 ± 0.09	
Launaea nudicaulis (L.) Hook. f.	Aerial parts	Hydro alcoholic	*E. coli*	-	20	[58]
			S. aureus	-	13	
		Butanol	*E. coli*	-	13	
			S. aureus	-	13	
		Ethyl acetate	*E. coli*	-	14	
			S. aureus	-	11	
Haplophyllum tuberculatum (Forssk.) A.Juss	Plant parts	Water	*E. coli*	-	8 ± 0.01	[59]
			H. influenza	-	8 ± 0.03	
			Pseudomonas	-	7 ± 0.02	

			S. aureus	-	7 ± 0.02	
		Methanol	*E. coli*	-	8 ± 0.06	
			H. influenza	-	6 ± 0.05	
			Pseudomonas	-	7 ± 0.07	
			S. aureus	-	-	
		Chloroform	*E. coli*	-	8 ± 0.05	
			H. influenza	-	10 ± 0.01	
			Pseudomonas	-	6 ± 0.88	
			S. aureus	-	6 ± 0.15	
		Ethyl acetate	*E. coli*	-	7 ± 0.04	
			H. influenza	-	6 ± 0.02	
			Pseudomonas	-	6 ± 0.01	
			S. aureus	-	6 ± 0.04	
		Butanol	*E. coli*	-	-	
			H. influenza	-	10 ± 0.02	
			Pseudomonas	-	8 ± 0.02	

			S. aureus	-	-	
		Hexane	*E. coli*	-	7 ± 0.05	
			H. influenza	-	8 ± 0.07	
			Pseudomonas	-	-	
			S. aureus	-	6 ± 0.02	
Maytenus dhofarensis Sebsebe	Stem bark	Hexane	*S. aureus*	-	10	[60]
			E. coli	-	-	
			K. pneumoniae	-	6	
		Chloroform	*S. aureus*	-	7	
			E. coli	-	7	
			K. pneumoniae	-	6	
		Ethyl acetate	*S. aureus*	-	10	
			E. coli	-	-	
			K. pneumoniae	-	6	
Psidium guajava L.	Leaves	Essential oil	*E. coli*	-	13 ± 0.23	[61]
			H. influenza	-	12 ± 0.91	

			P. aeruginosa	-	6 ± 0.23	
			S. aureus	-	12 ± 0.27	
			E. faecalis	-	6 ± 0.13	
Juniperus seravschanica Kom.	Leaves	Essential oil	*E. coli*	-	8.1 ± 0.1	[62]
			P. aeruginosa	-	13.2 ± 0	
			B. subtilis	-	12.4 ± 0.2	
			M. luteus	-	15.4 ± 0.2	
			S. aureus	-	13.2 ± 0.2	
			MRSA	-	9.9 ± 0.1	
		Methanol	*E. coli*	-	10.9 ± 0.1	
			P. aeruginosa	-	10.5 ± 0.5	
			B. subtilis	-	15.8 ± 0.3	
			M. luteus	-	13.5 ± 0.5	
			S. aureus	-	17.3 ± 0.6	
			MRSA	-	17.8 ± 0.3	
Millingtonia hortensis Linn.f.	Flowers	Essential oil	*Micrococcus luteus*	-	18.3 ± 0.21	[63]

			S. aureus	-	10 ± 0.94	
			P. aeruginosa	-	10.7 ± 0.59	
			E. aerogenes	-	23 ± 1.41	
			E. coli	-	7 ± 0.47	
			P. vulgaris	-	8.73 ± 0.58	
Azadirachta indica A. Juss	Stem	Ethyl acetate	*E. coli*	-	7 ± 0.21	[64]
			S. aureus	-	7 ± 0.37	
		Butanol	*P. aeruginosa*	-	7 ± 0.18	
		Methanol	*P. aeruginosa*	-	7 ± 0.17	
		Water	*P. aeruginosa*	-	6 ± 0.15	
Hyoscyamus gallagheri A.G.Mill. & Biagi	Leaves	Hexane	*E. coli*	-	10 ± 0.5	[65]
			K. pneumonia	-	8.5 ± 0.5	
			S. pneumonia	-	10 ± 1.03	
			S. aureus	-	9.5 ± 0.9	
		Chloroform	*E. coli*	-	11 ± 0.7	
			K. pneumonia	-	10.5 ± 0.8	

			S. pneumonia	-	8.5 ± 0.8	
			S. aureus	-	9.75 ± 1.0	
		Ethyl acetate	*E. coli*	-	10.5 ± 0.7	
			K. pneumonia	-	10.5 ± 0.9	
			S. pneumonia	-	12 ± 1.01	
			S. aureus	-	9.5 ± 0.8	
Pluchea arabica (Boiss) Qaiser & Lack.	Fresh twigs and flowers	Essential oil	*S. aureus*	-	8	[66]
			C. albicans	-	8	
			B. subtilis	-	7	
Zygophyllum luntii (Baker) Christenh. & Byng	Stem	Methanol	*E. coli*	-	3	[67]
			P. aeruginosa	-	14	
			S. aureus	-	3	
	Roots	Methanol	*E. coli*	-	8	
			P. aeruginosa	-	11	
			S. aureus	-	2	
	Leaves	Methanol	*E. coli*	-	11	

			P. aeruginosa	-	16	
			S. aureus	-	2	
	Leaves	Essential oil	*P. aeruginosa*	-	9	
			S. aureus	-	7	
Piper betle L.	Leaves	Hexane	*E. coli*	-	7	[68]
			P. aeruginosa	-	7	
			P. mirabilis	-	6	
			K. pneumonia	-	8.5	
			S. aureus	-	8	
			Streptococcus aglactiae	-	7	
		Dichloromethane	*E. coli*	-	7	
			P. aeruginosa	-	10	
			P. mirabilis	-	6	
			K. pneumonia	-	10	
			S. aureus	-	7	
			S. aglactiae	-	-	

		Ethyl acetate	*E. coli*	-	10	
			P. aeruginosa	-	10	
			P. mirabilis	-	6	
			K. pneumonia	-	9	
			S. aureus	-	8	
			S. aglactiae	-	-	
		Butanol	*E. coli*	-	6	
			P. aeruginosa	-	6.5	
			P. mirabilis	-	6	
			K. pneumonia	-	9	
			S. aureus	-	-	
			S. aglactiae	-	-	
		Aqueous	*E. coli*	-	7	
			P. aeruginosa	-	7	
			P. mirabilis	-	8	
			K. pneumonia	-	11	

			S. aureus	-	7.5	
			S. aglactiae	-	8	
Cleome austroarabica subsp. *muscatensis* D.F.Chamb. & Lamond	Aerial parts	Essential oil	*E. coli*	-	7	[69]
			H. influenza	-	6.5	
			P. aeruginosa	-	6	
			E. faecalis	-	7	
			S. aureus	-	7	
			S. pneumonia	-	7	
Thymus vulgaris L.	Leaves	Hydro alcoholic	*E. coli*	-	13	[70]
			S. aureus	-	8	
			P. aeruginosa	-	13	
			K. pneumoniae	-	15	
		Chloroform	*E. coli*	-	14	
			S. aureus	-	9	
			P. aeruginosa	-	9	
			K. pneumoniae	-	11	

		Petroleum ether	*E. coli*	-	13	
			S. aureus	-	20	
			P. aeruginosa	-	10	
			K. pneumoniae	-	15	
Dodonaea viscosa Jacq.	Leaves	Hexane	*E. coli*		6 ± 0.10	[71]
			H. influenza	-	5 ± 0.10	
			S. aureus	-	7 ± 0.19	
		Water	*E. coli*	-	6 ± 0.65	
			H. influenza	-	9 ± 0.14	
			S. aureus	-	8 ± 0.78	
		Butanol	*E. coli*	-	8 ± 0.67	
			H. influenza	-	7 ± 0.12	
			S. aureus	-	7 ± 0.27	
		Ethyl acetate	*E. coli*	-	6 ± 0.12	
			H. influenza	-	7 ± 0.53	
			S. aureus	-	7 ± 0.19	

		Methanol	*E. coli*	-	7 ± 0.14	
			H. influenza	-	7 ± 0.19	
			S. aureus	-	6 ± 0.16	
Zygophyllum simplex L.	Leaves	Hexane	*E. coli*	-	12.5 ± 0.10	[72]
			K. pneumonia	-	9 ± 0.10	
			S. aureus	-	10 ± 0.21	
			Streptococcus pseudopneumoniae	-	11 ± 0.09	
			Bacillus pumilus	-	12 ± 0.34	
		Ethyl acetate	*E. coli*	-	13.5 ± 0.89	
			K. pneumonia	-	10 ± 0.09	
			S. aureus	-	9.5 ± 0.14	
			S. pseudopneumoniae	-	10.5 ± 0.28	
			B. pumilus	-	12.5 ± 0.78	
		Dichloromethane	*E. coli*	-	11 ± 0.18	
			K. pneumonia	-	12.5 ± 0.56	
			S. aureus	-	10.5 ± 0.55	

			S. pseudopneumoniae	-	10.5 ± 0.90	
			B. pumilus	-	11.5 ± 0.26	
		Butanol	*E. coli*	-	12.5 ± 0.89	
			K. pneumonia	-	7.5 ± 0.09	
			S. aureus	-	9.5 ± 0.36	
			S. pseudopneumoniae	-	13 ± 0.14	
			B. pumilus	-	7.5 ± 0.88	
		Water	*E. coli*	-	13.5 ± 0.21	
			K. pneumonia	-	6.5 ± 0.15	
			S. aureus	-	9 ± 0.24	
			S. pseudopneumoniae	-	11.5 ± 0.25	
			B. pumilus	-	10 ± 0.24	
		Methanol	*E. coli*	-	8.5 ± 0.48	
			K. pneumonia	-	9.5 ± 0.80	
			S. aureus	-	8.5 ± 0.32	
			S. pseudopneumoniae	-	10 ± 0.38	

			B. pumilus	-	-	
(-) Not determined						

Antimicrobial activity of phytochemicals identified in Omani medicinal plants

The antimicrobial activity of plants stems from their secondary metabolites. Plant secondary metabolites include over 8,000 identified phenolic compounds, more than 12,000 alkaloids, and around 25,000 terpenoids, many of which exhibit potent antimicrobial activity [73]. Among these, phenolic compounds are frequently identified as antimicrobial agents [74]. Phenolic compounds can be further categorised into coumarins, phenolic acids, flavonoids, stilbenes, tannins and lignans. Among these, terpenoids and terpenes are broadly acknowledged for their antibacterial properties [75]. Alkaloids represent another significant class of plant-derived antibacterial compounds. They form a structurally diverse group that serves as the foundational framework for important antimicrobial drugs, including metronidazole and quinolones [76]. Table 3 outlines the antimicrobial activity of selected plant secondary metabolites identified in Omani medicinal plants.

Table 3: Antibacterial activity of secondary plant metabolites identified in Omani medicinal plants

Plant name	Compound group	Secondary metabolites	Antibacterial activity against	Mechanism	References
Ocimum basilicum	Phenolic acids	Rosmarinic acid	*P. aeruginosa*	Condensation and increased spatial division of DNA	[33, 77]
		Quinic acid	*S. aureus, S. pyogenes*, *P. aeruginosa*, *E. coli K. pneumoniae*	Not reported	[33, 78]
		Caffeic acid	*S. aureus*	Not reported	[33, 79]
		Protocatechuic acid	*S. aureus*, MRSA, *P. aeruginosa*, C. *acnes*	Not reported	[33, 80]
		Trans-ferulic acid	*S. chromogenes*, *B. amyloliquefaciens*, *K. pneumoniae*, *S. enteritidis*	Antibiofilm activity	[33, 81]

	Flavonoids	Naringenin	*S. aureus*	Damaging the bacterial cell membrane	[33, 82]
		Acacetin	MRSA	Not reported	[33, 83]
		Apigenin	*S. sanguinis*, *S. mutans*, *S. ratti*, *S. sobrinus*, *S. criceti*, *S. gordonii*, *S. anginosus*, *F. nucleatum*, *P. gingivalis*	Not reported	[33, 84]
		Luteolin	*S. aureus*, *L. monocytogenes*	Antibiofilm activity	[33, 85]
		Rutin	*E. faecalis*, *S. pyogenes*, *P. aeruginosa*, *B. cereus*, *E. coli*, *K. pneumoniae*	Not reported	[33, 86]
Teucrium polium	Flavonoids	Cirsiliol	MRSA, methicillin-resistant Staphylococcus epidermis	Inhibit ATP synthase and decrease the intracellular levels of ATP	[33, 87]
Commiphora gileadensis	Flavonoids	Eriodictyol	*P. aeruginosa*	Antibiofilm activity	[34, 88]

		Isovitexin	*S. aureus*	Inhibit the activity of Sortase A	[34, 89]
		Catechin Gallate	*S. aureus*, *E. coli*, *Salmonella*, *A. pyogenes*	Not reported	[34, 90]
		Orientin	*S. aureus*, *P. aeruginosa*, *E. coli*, *E. faecalis*	Not reported	[34, 91]
		Isoorientin	*S. aureus*, *P. aeruginosa*, *E. coli*, *E. faecalis*	Not reported	[34, 91]
		Quercetin	*S. aureus*, *P. aeruginosa*, *E. coli*, *E. faecalis*	Not reported	[34, 91]
Datura metel	Terpene	Squalene	*E. coli*, *S. aureus*, *P. putida*	Not reported	[36, 92]
Terminalia dhofarica	Phenolic acid	Gallic acid	*P. aeruginosa*, *S. aureus*, *E. coli*, *L. monocytogenes*	Irreversible changes in membrane properties	[39, 93]

		Coumaric acid	*S. pneumoniae*, *B. subtilis*, *S. aureus*, *S. dysenteriae*, *E. coli*, *S. typhimurium*	Increased plasma membrane permeability, inhibition of cellular functions through binding to genomic DNA.	[39, 94]
	Tannin	Punicalagin	*V. parahaemolyticus*, *S. aureus*	Damaged to the cytoplasmic membrane, inhibits biofilm activity	[39, 95, 96]
		Corilagin	*S. aureus*, *E. coli*	Altered membrane permeability	[39, 97]
		Ellagic acid	*E. coli*, MRSA, *P. aeruginosa*	Not reported	[39, 98]
Boswellia sacra	Terpene	Limonene	*S. aureus*	Increased membrane permeability and damage to respiratory metabolism	[40, 99]
		Terpineol	*E. coli*, *L. monocytogenes*, *S. typhimurium*, *S. aureus*	Altered membrane permeability	[40, 100]
		α-pinene	*E. coli*, *P. aeruginosa*, *S. aureus*,	Not reported	[40, 101]
		Linalool	*P. fluorescens*	Damaged to the membrane	[40, 102]

		α-Terpineol	*E. coli*	Damage associated with morphological changes	[40, 103]
		Terpinen-4-ol	*S. mutans*, *L. acidophilus*	Antibiofilm activity	[40, 104]
		Carvacrol	*B. cereus*	Not reported	[40, 105]
		Thymol	*S. aureus, E. coli, C. perfringens*	Not reported	[40, 106]
		Caryophyllene	*B. cereus*	Increase in the membrane permeability	[40, 107]
		Humulene	*B. fragilis*	Antibiofilm activity	[40, 108]

Challenges and limitations in translating plant-derived antimicrobial activity

Antibacterials derived from medicinal plants, including those from Oman, are generally safer, cost-effective, readily available within local communities and capable of providing significant therapeutic benefits [109]. Nevertheless, using natural plant extracts as antibacterial agents presents intrinsic challenges. Medicinal plant compounds should be used with caution when evidence for their efficacy is insufficient [110]. Toxicological and clinical studies demonstrating their safety and efficacy can be limited [73]. Variables such as cultivation region, harvest season, processing methods, and plant parts can also influence the activity and composition of compounds present in medicinal plant extracts [110]. Scientists also struggle to fully elucidate the complex interactions among the numerous compounds in a medicinal plant. Comprehensive characterisation of plant extract composition remains challenging, as these extracts contain numerous constituents that complicate interpretation. Isolating specific compounds with the required antibacterial properties can be time-consuming and may necessitate large amounts of plant material.

The progression from *in vitro* studies to *in vivo* experiments and, ultimately, to human clinical trials remains a major obstacle to the advancement of new antibacterials. Although several compounds have been identified in antibacterial Omani medicinal plants (Table 3), none of them is currently in clinical use. This may be because plant compounds often rely on complex synergistic interactions among multiple constituents to enhance the activity of the bioactive compounds. Several studies have demonstrated that the overall activity of plant extracts may arise from mixtures of compounds exhibiting antagonistic, additive, or synergistic effects [111]. Therefore, a major concern in developing antibacterials from medicinal plants is the potential for antagonistic or synergistic effects arising from the complex composition of the extracts [111]. Synergism within and between plant extracts has been extensively reviewed, with evidence suggesting that, in some cases, the combined effect of plant mixtures exceeds the simple sum of their individual components [112]. However, such combinations may also result in antagonism, potentially reducing or negating the therapeutic effect [112]. Classifying combinational effects in complex mixtures and identifying the compounds responsible remains a challenging task. Therefore, the use of bioassays to identify mixtures or compounds responsible for specific biological activity is of great importance [113]. The demand for effective, new, safer, and affordable antibacterials has become paramount in developing new antimicrobial therapies.

Another challenge in the use of medicinal plants as antimicrobial agents is their potential toxicity [114]. Most of these extracts have not been assessed by the United States Food and Drug Administration (FDA) [115]. The absence of reliable data on the actual toxicity of many plant extracts is therefore a matter of concern, as the adverse effects resulting from the misuse of medicinal plants constitute a recognised public health issue [115]. Another challenge in developing antibacterials from medicinal plants is the insufficient financial support for research, which contributes to a lack of high-quality studies on structure-activity relationships of individual compounds [116]. Despite these challenges, there remains a strong demand for the development of new antibacterials derived from traditional medicinal plants.

Future perspectives

Medicinal plants remain an insufficiently explored source of bioactive compounds, with only a small fraction of their properties having been studied to date. As many medicinal plants, including those from Oman, remain unexplored, they represent an important natural resource for the development of novel resistance-modifying compounds with potential therapeutic applications. However, a substantial portion of complex medicinal plant mixtures remains chemically unexplored, representing a resource with significant potential for further scientific study. This may be followed in

the future in *in vivo* models to assess the clinical relevance of these phytochemicals and establish a valid correlation with *in vitro* efficacy results [117]. Future studies should also focus on structural modification of phytochemicals to enhance pharmacodynamic and pharmacokinetic properties, as well as structure-activity relationship analysis. Synergistic interactions within medicinal plant extracts, as well as between phytochemicals and antibiotics, should also be investigated to elucidate mechanisms underlying antibacterial activity and to identify multiple potential therapeutic targets. The interaction between antimicrobial agents and medicinal plant extracts may be synergistic or antagonistic. Therefore, further studies, particularly *in vivo* investigations and toxicity assessments, are required for these medicinal plants to be recognised as potential antibacterial agents.

Conclusion

This review highlights the potential efficacy of Omani medicinal plants as an alternative therapy for addressing the emergence and spread of multidrug-resistant pathogens. However, this study highlights the inadequate characterisation of the chemical composition of antibacterial medicinal plants in Oman. Only a limited number of Omani medicinal plants have had their bioactive components investigated. The lack of such analysis undermines the validity of claims made in the ethnomedicinal system. Given the vast therapeutic potential of medicinal plants, research is needed to generate unique chemical fingerprints and identify novel compounds in Omani medicinal plants. A deeper molecular-level understanding of synergistic interactions among phytochemical combinations in Omani medicinal plants could reduce antibiotic use and help prevent and overcome drug-resistant pathogens.

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The authors have no competing interests to declare that are relevant to the content of this article.

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Author contributions

MJYZ: conceptualisation, original draft writing, investigation, reviewing and editing, investigation and formal analysis; FK: conceptualisation, reviewing and editing; LR: supervision, reviewing and editing.

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