



A Comprehensive Review on the Role of Medicinal Plants as Antimicrobial Agents

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Abstract

The emergence of antimicrobial resistance (AMR) presents a worldwide health crisis, highlighting the urgent need for new alternative therapeutic options. Through the course of human history, many have relied on medicinal plants as the traditional source of health care, and they continue to be used as effective primary healthcare resources, providing bioactive compounds possessing antimicrobial activity. The intention of this comprehensive review is to detail the proposed role of medicinal plants in the development of antimicrobial agents by discussing phytochemical diversity, mechanisms of action, extraction methods, and the potential for synergy with conventional antibiotics. In addition, this review will include current technological advancements in the application of nanotechnology and molecular docking methods. Medicinal plant secondary metabolites including alkaloids, flavonoids, terpenoids, tannins, phenolics, and saponins have documented broad-spectrum activities against pathogenic bacteria, fungi, and viruses. Evidence indicates that antimicrobial activity of plant-derived compounds occurs via several mechanisms including the disruption of the cell membrane, inhibition of protein synthesis, interference with nucleic acid replication, and/or suppression of quorum sensing. In addition, synergistic interactions are expected between plant-based products and conventional antibiotics in efforts to create alternatives to combat multidrug-resistant organisms. While significant progress has been made in the development of plant-based antimicrobial agents, standardization, safety/toxicity assessment, clinical validation, and regulatory approval remain substantial obstacles. This review emphasizes the scientific importance of medicinal plants as a potential source of new antimicrobial drugs, and provides a perspective on the integration of traditional medicinal knowledge with current biomedical research toward the successful development of new strategies to address antibiotic resistance.

Keywords: Medicinal plants, antimicrobial activity, phytochemicals, antibiotic resistance, plant extracts, ethnopharmacology, natural therapeutics

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Introduction

For many years, Antimicrobial Resistance (AMR) was a long term problem. During the 21st century, AMR has become one of the biggest public health threats around the world. Many multidrug-resistance (MDR) pathogens are being seen today as a result of the use of antibiotics, making traditional antibiotic treatments less effective, extending the duration of illnesses, and increasing the death rates associated with these diseases and the costs associated with their treatment. According to the World Health Organization (WHO), the impact of AMR contributes to millions of deaths each year and is an obstacle to advances in modern medicine including the ability to conduct routine surgeries, treat cancer using chemotherapy, and perform organ transplants (WHO, 2023). Overuse and misuse of antibiotics in both human health care, veterinary medicine and agriculture has led to the development of bacterial strains that are resistant to the first line of treatment as well as to the last-resort treatment options (Ventola, 2015). Many bacteria such as *Staphylococcus aureus*, *Escherichia coli*, *Klebsiella pneumoniae*, and *Pseudomonas aeruginosa* have developed resistances against multiple different antibiotic classes such as beta-lactams, aminoglycosides, and fluoroquinolones. The emergence of Methicillin Resistant *Staphylococcus aureus* (MRSA), Extended Spectrum Beta Lactamase (ESBL)-producing

bacteria, and Carbapenem-resistant Enterobacteriaceae represent the seriousness of this issue (Prestinaci *et al.*, 2015). The advance of new antifungal treatments such as candida auris is complicated further by the emergence of virulent viral strains that have developed resistance to antiviral medications. In addition to the slow development and high cost of developing new antibiotics, regulatory barriers add to the complications associated with this urgent need for alternative anti-microbial treatments (Newman & Cragg, 2020). For thousands of years, many cultures have relied upon traditional medicinal plants as their primary healthcare resources through formal forms of traditional medicine including Ayurveda, Unani, Siddha, and Traditional Chinese Medicine. These systems always rely heavily upon formulations derived from plants to treat infectious diseases, inflammation, and chronic conditions. An estimated 80% of the global population, especially in developing nations, regularly rely on herbal medicine as a source of basic health care (WHO, 2023). The traditional ethnopharmacological knowledge accumulated from the experiences of generations will provide a wealth of information regarding the therapeutic potential of many different plant species. Many plants will create a wide variety of secondary metabolites to protect themselves from

microbial pathogens, herbivores, and environmental stresses. The vast majority of these bioactive compounds are composed of alkaloids, flavonoids, terpenoids, phenolic acids, tannins, saponins, and glycosides, and have been shown to possess significant antibacterial activity *in vitro* and *in vivo* (Cowan, 1999; Cushnie *et al.*, 2014). While traditional antibiotics generally attack one pathway in the microbe, many plant-based compounds are believed to connect to multiple pathways and offer multiple ways for microbes to gain resistance against them (Gibbons 2008). For instance, several flavonoids can simultaneously disrupt microbial membranes, inhibit nucleic acid synthesis, and affect the metabolism of energy (Daglia 2012). Such multi-targeted activity suggests that plant-based compounds could be important tools in the treatment of multiple drug-resistant organisms. Historically, natural products have played a major role in the discovery of modern-day pharmaceuticals; approximately 25%-30% of all currently used pharmaceuticals are derived from plants (Newman & Cragg 2020). Well-known examples include quinine - a natural product derived from the bark of several *Cinchona* species; artemisinin - a natural product from *Artemisia annua*; and morphine - a natural product from the opium poppy (*Papaver somniferum*). In the mid-20th century, with the introduction of penicillin and the shift to synthetic antibiotics, research into botanicals as alternative therapies had declined; however, the recent resurgence of bacteria with antibiotic-resistant infections has rekindled interest in botanicals as potential alternatives to synthetic antibiotics. The modern microbiology laboratory employs traditional methods along with modern sophisticated techniques, including high-performance liquid chromatography (HPLC), mass spectrometry, molecular docking, and genomic analysis, to evaluate the potential of phytochemicals as antimicrobial agents by identifying and characterizing novel phytochemicals with antimicrobial activity. Recent scientific studies have confirmed the ability of extracts from plants to inhibit bacterial growth, inhibit biofilm formation, alter quorum sensing pathways, and inhibit the action of efflux pumps - mechanisms by which bacteria develop resistance to treatment with antibiotics (Stermitz *et al.*, 2000; Gupta & Birdi, 2017). Many types of pathogenic bacteria can form biofilm, a crucial component of virulence, causing long-term infections and making treatment with antimicrobials more difficult. Phytochemicals (phenolic acids, essential oils, etc.) have been shown to effectively inhibit biofilm formation, therefore increasing the antibiotic activity of conventional antibiotics (Bakkali *et al.*, 2008). There are also reports of synergistic interactions with plant extracts and antibiotics that can restore antibiotic susceptibility in resistant bacteria. Plant-derived compounds have antibacterial activity, but also exhibit antifungal and antiviral properties. Between curcumin, eugenol, and allicin, there is strong inhibitory activity against numerous fungal pathogens (*Candida albicans*, dermatophytes) and viruses (influenza, herpes simplex virus) (Hewlings & Kalman, 2017). Due to their many beneficial properties, plant-based antimicrobials hold great potential for use as part of infectious disease management across multiple facets of the infectious disease community. Nanotechnology can also be used to enhance research into plant-based antimicrobials. Eco-friendly green synthesis of nanoparticles with plant extracts is garnering interest among researchers for its ability to create products with enhanced antimicrobial activity (Irvani *et al.*, 2014).

This nano-formulation will improve bioavailability, stability, and specificity of phytochemicals, allowing for effectiveness of plant-derived antimicrobials to overcome the limitations of traditional herbal products. Despite promising findings from laboratory studies, there are many hurdles to the successful application of plant-based antimicrobials in the clinical setting. The variability in phytochemicals due to environmental differences as a result of the lack of standardized protocols for extraction and limited pharmacokinetic information about the 19560 truly works wonderfully! However, these obstacles (primarily the absence of large-scale, well-controlled human clinical studies) prevent most researchers from validating their hypotheses about which specific medicinal plants provide effective antimicrobial activity. The fact that every country has its own regulations for herbal medicines further complicates this process and decreases the ability for the successful commercialization of effectively researched antimicrobial agents worldwide. The rise of antimicrobial resistance combined with the enormous amount of unutilized pharmaceutical value associated with nature-based products merits the execution of comprehensive and collaborative research programs to identify effective and safe antimicrobial agents sourced from plants that can serve humanity's needs. This review will provide an overview of the available literature on the antimicrobial properties of medicinal plants, focusing on the diversity of phytochemicals in these plants, their modes of antimicrobial action against bacteria, and their potential for combining with each other to increase their efficacy. The potential of ethnopharmacology when combined with modern techniques may be the key to resolving the increasing global crisis associated with antibiotic resistance.

Review of Literature

Antimicrobial properties of medicinal plant products have increasingly come into focus during the past two decades with the growing problem of antimicrobial resistance (AMR). Many studies conducted *in vitro* and *in vivo* show that these natural products have activity against a wide variety of microorganisms (both pathogenic and nonpathogenic) including bacteria, fungi and viruses. Evidence from the field of ethnopharmacology shows how traditional ethnomedical systems, such as Ayurvedic Medicine, Chinese Herbal Medicine and African Herbal Medicine, have identified plant sources with antimicrobial activity and have been used to treat infectious diseases over thousands of years. Rates (2001) indicates that approximately 50% of all commercially available pharmaceuticals have their origins in natural products providing additional support for the importance of using ethnobotanical knowledge. Cowan (1999) further supports the idea that antimicrobial agents found in plant products are sources for antimicrobial agents due in part to the complex chemistry that makes up this type of product. Most of the research conducted prior to the 2000's focused primarily on using crude extracts as a source of antimicrobial materials; however modern methods of phytochemical analysis have permitted the identification of specific constituents responsible for the antimicrobial activity found in medicinal plants.

Research has shown that medicinal plants have strong antibacterial properties against both Gram + and Gram - bacteria. Generally, Gram + bacteria are more susceptible to this activity than Gram - bacteria because there is less complexity of their cell wall structure than that of Gram -

bacteria. Gram - bacteria have a second outer membrane layer that restricts the permeability of compounds being able to get through to them (Bakkali *et al.*, 2008).

Flavonoids and alkaloids inhibit the activity of two critical enzymes involved in bacterial DNA replication, gyrase and topoisomerase (Cushnie *et al.*, 2014). An example of such an effect is berberine; it inhibits the growth of *Staphylococcus aureus* and *Escherichia coli*. In addition, phenolic acids can disrupt the permeability of the bacterial membrane as well as inhibit energy metabolism within the bacterial cell (Daglia, 2012).

Gibbons's (2008) work found that phytochemicals have an effect on the bacteria's efflux pump, which is a primary factor contributing to antibiotic resistance. Plant-derived efflux pump inhibitors lead to increases in the concentration of antibiotics within cells, thus regaining the ability for resistant strains to be affected by antibiotics (Stermitz *et al.*, 2000). The most recent studies conducted (2015-2024) have focused on the prevention of biofilms forming. Bacterial biofilms are used by bacteria to protect themselves from antibiotics and/or the host's immune system. Essential oils extracted from certain plants like oregano and thyme have successfully inhibited biofilm development in *Pseudomonas aeruginosa* (Nazzaro *et al.*, 2013). The number of fungal infections continues to grow around the world and will continue to do so among patients who are immunocompromised. Medicinal plants provide compounds that can inhibit fungal infections by interfering with ergosterol synthesis, maintaining the cell membrane integrity, and affecting mitochondrial function. Curcumin, derived from *Curcuma longa*, has been shown to have antifungal properties against *Candida albicans* by increasing oxidative stress within the fungal cell, leading to its membrane becoming disrupted (Hewlings & Kalman, 2017). Allicin, which is a compound derived from the garlic plant (*Allium sativum*), has been found to inhibit the activity of thiol-based enzymes found in fungal cells (Ankri & Mirelman, 1999). Essential oils that are high in terpenoids disrupt the ability of fungal cells to absorb nutrients through their cell membranes and prevent the formation of spores (Bakkali *et al.*, 2008). Based on the evidence presented above, plant-derived antifungal agents may serve as a new alternative to existing treatments for resistant fungal infections.

The ability of plant-based materials to be effective against viruses is also present in compounds from plants processed to make them liquid (e.g. hot water infusion); examples include flavonoids and polyphenols, both of which have shown inhibitory effects on viral reproduction through both blocking viral entry into cells and interfering with nucleic acid production (Zakaryan *et al.*, 2017). As an example of both of these types of compounds, curcumin has been shown to inhibit the influenza virus and herpes simplex virus (Hewlings & Kalman, 2017).

With the COVID-19 pandemic, multiple phytochemicals have been studied using molecular docking studies to determine their potential to inhibit Sars-Cov-2 proteases (Sharma *et al.*, 2020); while there has not yet been sufficient clinical validation, results from both in silico and in vitro studies support the hypothesis that these medicinal plants may have antiviral properties.

Significant progress has been made in research that targets plant-derived compounds to reverse resistance mechanisms to traditional antibacterial agents. Resistance to antibacterials occurs for a variety of reasons, such as increased production

of efflux pumps, the enzymatic destruction of antibacterials by the bacteria themselves, and mutations at the target site of action (Ventola, 2015).

An example of a plant-derived compound that has been shown to reverse antibiotic resistance is reserpine and berberine analogs, both of which have been demonstrated to inhibit efflux pump function in gram-positive bacteria (Stermitz *et al.*, 2000). Further research by Gupta and Birdi (2017) indicates that extracts from some medicinal plants can augment the effects of antibacterials when used in a combination therapy approach.

The emerging scientific field of quorum sensing inhibition involves disrupting the regulatory mechanisms regulating bacterial virulence and biofilm development. Flavonoids and phenolic compounds reduce pathogenicity by disrupting the quorum sensing signaling pathways and will not create a selection pressure for the development of resistance (Gibbons, 2008). Combination therapy (use of plant extracts plus antibiotics) has demonstrated potential benefits due to synergistic interactions that enhance the effectiveness of antibiotics, lead to lower dosages, and/or result in reduced side effects.

Several studies have shown that garlic extract increases the activity of tetracycline against resistant bacteria (Ankri & Mirelman, 1999). In addition, various extracts from *Azadirachta indica* (neem) have synergistic effects with β -lactam antibiotics (Biswas *et al.*, 2002). Synergistic interactions may result from increasing membrane permeability, inhibiting enzymes or inhibiting efflux pumps feeding back to their cell surface (Gupta & Birdi, 2017).

Nanotechnology is being integrated with phytochemistry. Plant extracts and biological materials are being used for the green synthesis of silver nanoparticles (Iravani *et al.*, 2014). The larger surface area of the nanoparticles increases the ability to interact with bacteria.

Bioavailability, the ability of materials to be delivered to specific locations in the body, and sustained release of plant-based nanoparticles is superior to crude extracts of herbal materials. New approaches will help overcome limitations of crude extracts from plants.

Many studies show the antimicrobial effects of plants in vitro; however, clinical trials have been limited, especially because variability in phytochemical composition based on region and environmental conditions make reproducibility difficult (Rates, 2001).

Several clinical studies have evaluated standardized herbal medicines for skin infections and oral hygiene, but further large-size randomized controlled studies are required to verify their safety and effectiveness.

The current body of literature has numerous research limitations such as:

- Unclear methods of producing herbal extracts
- Variation amongst concentrations of the active chemical compounds in different herbal products
- Limited information available about how the body breaks down and absorbs herbal products
- Limited toxicology data
- Lack of consistent regulatory standards for the production of herbal products

For the advancement of clinical treatment of diseases, addressing the gaps in the clinical literature is needed in order to turn scientific data into clinical treatments.

Recent research trends emerging from the above-mentioned limitations of herbal research include:

- Screening of herbal medicines using genomic methods
- Molecular docking studies using computer-generated simulation programs with the help of artificial intelligence
- Use of plant-based compounds to inhibit efflux pumps in bacteria
- Further studies to determine the medicinal value of underutilized ethnomedicinal plants
- Development of nanoemulsion formulations of herbal medicines to aid in the delivery of medications at a targeted rate.

Phytochemical Diversity and Antimicrobial Properties

Plants produce diverse bioactive compounds:

Alkaloids-Nitrogen-containing compounds that inhibit DNA replication and enzyme activity (Cushnie *et al.*, 2014).

Flavonoids-Polyphenolic compounds that disrupt membranes and inhibit nucleic acid synthesis (Daglia, 2012).

Terpenoids-Lipophilic molecules that compromise membrane integrity (Bakkali *et al.*, 2008).

Tannins-Bind to microbial proteins and enzymes (Scalbert, 1991).

Phenolic acids-Induce oxidative stress and biofilm inhibition (Gibbons, 2008).

Table 1. Major Phytochemicals and Their Antimicrobial Mechanisms

Phytochemical Class	Mechanism of Action	Target Microorganisms	Key References
Alkaloids	DNA intercalation, enzyme inhibition	Gram+ bacteria	Cushnie <i>et al.</i> , 2014
Flavonoids	Membrane disruption	Gram± bacteria	Daglia, 2012
Terpenoids	Lipid membrane damage	Bacteria & fungi	Bakkali <i>et al.</i> , 2008
Tannins	Protein precipitation	Bacteria	Scalbert, 1991
Phenolics	Oxidative stress induction	Biofilm-forming bacteria	Gibbons, 2008

Mechanisms of Antimicrobial Action

Plant-derived antimicrobials act via:

- Cell wall disruption
- Cytoplasmic membrane permeability alteration
- Inhibition of protein synthesis
- Inhibition of nucleic acid synthesis
- Efflux pump inhibition
- Quorum sensing suppression
- Biofilm inhibition

Multi-target mechanisms reduce resistance probability (Stermitz *et al.*, 2000; Ventola, 2015).

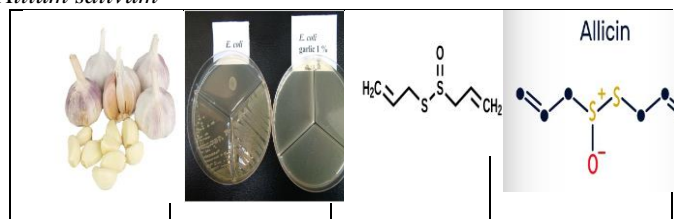
Important Medicinal Plants with Proven Activity

Azadirachta indica



Contains azadirachtin and nimbidin; effective against Staphylococcus aureus and Escherichia coli (Biswas *et al.*, 2002).

Allium sativum



Allicin exhibits broad-spectrum antibacterial and antifungal activity (Ankri & Mirelman, 1999).

Curcuma longa



Curcumin inhibits microbial protein synthesis and biofilm formation (Hewlings & Kalman, 2017).

Table 2. Selected Medicinal Plants and Their Antimicrobial Spectrum

Plant	Active Compound	Target Pathogens	Reported Activity
Neem	Azadirachtin	S. aureus, E. coli	Antibacterial
Garlic	Allicin	MRSA, Candida	Broad-spectrum
Turmeric	Curcumin	Gram± bacteria	Anti-biofilm
Tulsi	Eugenol	Fungi, bacteria	Antifungal
Aloe vera	Anthraquinones	E. coli	Antibacterial

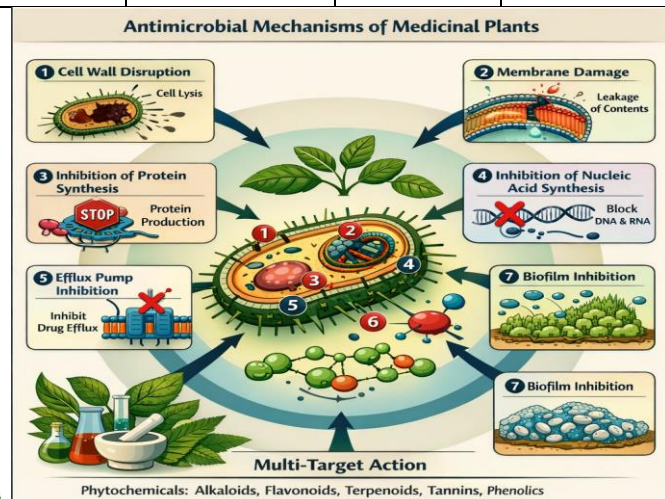


Figure 1. Antimicrobial mechanisms of medicinal plant-derived phytochemicals.

Schematic representation illustrating the multi-target antimicrobial actions of bioactive phytochemicals derived from medicinal plants. Major mechanisms include (1) disruption of microbial cell wall integrity leading to cell lysis, (2) cytoplasmic membrane damage resulting in leakage

of intracellular contents, (3) inhibition of protein synthesis through ribosomal interference, (4) suppression of nucleic acid synthesis affecting DNA and RNA replication, (5) efflux pump inhibition enhancing intracellular drug retention, and (6) prevention of biofilm formation and quorum sensing pathways. Collectively, phytochemicals such as alkaloids, flavonoids, terpenoids, tannins, and phenolic compounds exert broad-spectrum antimicrobial effects via multi-target actions, reducing the likelihood of resistance development.

Synergistic Effects with Antibiotics

Plant extracts enhance antibiotic effectiveness by:

Efflux pump inhibition (Stermitz *et al.*, 2000)

Biofilm disruption (Gupta & Birdi, 2017)

Membrane permeability enhancement

Combination therapy shows promising results against MDR pathogens.

Nanotechnology and Modern Advances

Green synthesis of nanoparticles using plant extracts improves antimicrobial potency (Iravani *et al.*, 2014).

Nanoparticles enhance surface interaction and stability.

Table 3. Modern Approaches in Plant-Based Antimicrobial Research

Approach	Application	Advantage
Nanoparticles	Enhanced delivery	Increased potency
Molecular docking	Target identification	Mechanistic clarity
Biofilm assays	Resistance study	Clinical relevance
Combination therapy	MDR treatment	Reduced resistance

Clinical and Pharmacological Challenges

- Standardization issues (Rates, 2001)
- Toxicity concerns
- Pharmacokinetic variability
- Regulatory barriers

Future Prospects

- Genome-guided phytochemical screening
- Herbal nanoformulations
- Clinical trials of standardized extracts
- Development of plant-derived efflux pump inhibitors

Discussion

A growing number of people are becoming resistant to antibiotics worldwide, which is leading to a heightened demand for novel therapies that go beyond traditional antibiotics. A review of the literature on medicinal plants provides substantial evidence that they can supply valid and effective natural sources of antimicrobials. The phytochemicals found in plants have a wide variety of different chemical structures and therefore a multiple mode of action, which makes them a more effective alternative to the single-target action of conventional synthetic antibiotics. The need for traditional antibiotics is especially urgent when dealing with multi-drug resistant pathogens, as many of the resistance mechanisms employed by these pathogens render conventional antibiotics ineffective (Ventola, 2015). The major benefit of plant-derived antimicrobials, in comparison to synthetic antibiotics, is their chemical complexity. Most synthetic antibiotics are designed with the intention of inhibiting the activity of one important enzyme or metabolic pathway, but many of the phytochemicals found in plants are able to inhibit multiple enzymes or metabolic pathways. For

instance, flavonoids stop the growth of many types of microorganisms by disrupting their cell membranes as well as by inhibiting the synthesis of nucleic acids and the metabolism of energy (Daglia, 2012). In a similar fashion, terpenoids disrupt the integrity of microbial cell membranes while also inhibiting the function of enzymes involved in the electron transport chain (Bakkali *et al.*, 2008). By using multiple targets within the same pathogen, this multi-target approach decreases the likelihood that the pathogen will develop a resistance mechanism, since it will have to simultaneously develop resistance to multiple inhibitory mechanisms. Another critical finding from contemporary research is the role of plant-derived compounds in modulating bacterial resistance mechanisms. Efflux pumps are one of the primary contributors to antimicrobial resistance, enabling bacteria to expel antibiotics before they reach effective intracellular concentrations. Stermitz *et al.* (2000) demonstrated that plant-derived efflux pump inhibitors can restore antibiotic susceptibility in resistant strains. Subsequent research has confirmed that certain alkaloids and flavonoids act synergistically with antibiotics by blocking efflux pump activity (Gupta & Birdi, 2017). This synergy suggests that medicinal plants may not only function as standalone antimicrobials but also serve as resistance-modifying agents. Biofilm formation presents another major challenge in antimicrobial therapy. Biofilms protect microorganisms from antibiotics and host immune responses, contributing to chronic and recurrent infections. Essential oils and phenolic compounds derived from medicinal plants have demonstrated significant biofilm inhibition properties (Gibbons, 2008). By interfering with quorum sensing pathways, phytochemicals reduce bacterial virulence without exerting strong selective pressure, potentially slowing resistance evolution. This mechanism is particularly important because quorum sensing inhibitors target communication pathways rather than essential survival processes, thereby reducing the likelihood of resistance development. The antifungal potential of medicinal plants further broadens their therapeutic relevance. Fungal pathogens, particularly in immunocompromised individuals, pose increasing clinical challenges. Compounds such as curcumin from *Curcuma longa* and allicin from *Allium sativum* exhibit significant antifungal effects through oxidative stress induction and enzyme inhibition (Ankri & Mirelman, 1999; Hewlings & Kalman, 2017). Given the limited number of effective antifungal drugs and rising resistance, plant-derived antifungal agents may offer valuable therapeutic alternatives. The antiviral activity of phytochemicals has also gained considerable attention, particularly in light of emerging viral pandemics. Polyphenols and flavonoids have been shown to inhibit viral replication by interfering with viral entry, protease activity, and nucleic acid synthesis (Zakaryan *et al.*, 2017). During the COVID-19 pandemic, several plant-derived compounds were evaluated through molecular docking studies for their potential inhibitory effects against SARS-CoV-2 enzymes (Sharma *et al.*, 2020). Although clinical validation remains limited, these findings underscore the broad-spectrum antimicrobial potential of medicinal plants. Despite promising in vitro findings, translation into clinical practice remains challenging. One major limitation is variability in phytochemical composition. Environmental conditions, soil quality, climate, harvesting time, and extraction methods significantly influence the concentration of bioactive

compounds (Rates, 2001). This variability complicates standardization and reproducibility, which are essential for pharmaceutical development. Unlike synthetic drugs with defined molecular structures, plant extracts often contain complex mixtures of compounds, making dosage optimization and pharmacokinetic evaluation more difficult. Toxicological assessment is another crucial concern. While medicinal plants are often perceived as safe due to their natural origin, certain phytochemicals can exhibit cytotoxic or genotoxic effects at higher concentrations. Comprehensive toxicological studies and long-term safety evaluations are required before large-scale clinical application. Additionally, herb-drug interactions must be carefully evaluated, particularly when plant extracts are used in combination therapy. Regulatory frameworks governing herbal medicines vary significantly across countries, posing additional barriers to commercialization. In many regions, herbal products are categorized as dietary supplements rather than pharmaceutical agents, resulting in less stringent quality control measures. Establishing standardized guidelines for extraction, purification, dosage, and quality assurance is essential for ensuring therapeutic reliability. Recent advancements in nanotechnology offer promising solutions to some of these challenges. Green synthesis of nanoparticles using plant extracts enhances antimicrobial efficacy by improving bioavailability and targeted delivery (Iravani *et al.*, 2014). Nanoformulations protect phytochemicals from degradation and enable sustained release, thereby improving therapeutic outcomes. Furthermore, integration of molecular docking and computational biology has facilitated the identification of potential phytochemical targets, accelerating drug discovery processes. The synergistic potential of plant extracts with conventional antibiotics represents a particularly promising avenue for future research. Combination therapy can reduce antibiotic dosage requirements, minimize adverse effects, and restore efficacy against resistant strains. Studies have demonstrated that extracts from *Azadirachta indica* enhance the activity of β -lactam antibiotics against resistant bacteria (Biswas *et al.*, 2002). Such findings highlight the potential of medicinal plants as adjunct therapies in modern antimicrobial treatment protocols. Another emerging research direction involves genome-guided phytochemical screening. Advances in genomics and metabolomics enable identification of plant species with high concentrations of bioactive compounds. Artificial intelligence and machine learning tools are increasingly being used to predict antimicrobial activity and optimize compound selection. These interdisciplinary approaches integrate ethnobotany, molecular biology, pharmacology, and computational science, expanding the scope of plant-based antimicrobial research. From a public health perspective, plant-based antimicrobials may offer cost-effective and sustainable solutions, particularly in low- and middle-income countries where access to modern antibiotics is limited. Local cultivation of medicinal plants reduces dependency on imported pharmaceuticals and supports community-based healthcare systems. However, large-scale cultivation must be managed sustainably to prevent overharvesting and biodiversity loss. Overall, the discussion highlights that medicinal plants possess significant antimicrobial potential supported by extensive laboratory evidence. Their multi-target mechanisms, resistance-modulating effects, and synergistic interactions provide clear advantages over single-target synthetic antibiotics.

Nevertheless, clinical translation requires rigorous standardization, toxicological evaluation, and regulatory harmonization. Bridging the gap between traditional knowledge and modern scientific validation remains essential for realizing the full therapeutic potential of medicinal plants in combating antimicrobial resistance.

Conclusion

Medicinal plants represent a vast and underexplored reservoir of antimicrobial agents capable of addressing global antibiotic resistance. Their diverse phytochemical constituents and multi-target mechanisms provide significant therapeutic advantages. Integrating ethnopharmacology, molecular biology, and nanotechnology may accelerate drug discovery and development. However, rigorous standardization, toxicological evaluation, and clinical validation are essential for global therapeutic acceptance.

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