# Efficacy of Spices, Peptides, and Essential Oils Against Resistant Microbes from Plant-Derived Antimicrobials – A Review

Saira Sameen [1*], Kausar Hussain Shah [2], Tariq Rasheed [1], M. Usama Khalil [1], M. Bilal Khalil [1]

## Abstract

Microbial resistance to antibiotics has become a significant challenge due to factors such as excessive exposure to antibiotics, which leads to genetic mutations, decreased permeability, and other adaptive mechanisms in microbes. Plants, with their rich array of anti-infective compounds, offer promising alternatives for addressing this issue. This review highlights the antimicrobial potential of various plant-derived substances, including antimicrobial peptides, spices, and essential oils. Spices, in particular, have demonstrated considerable antimicrobial efficacy owing to their unique structural components. For example, methanol extracts from certain spices have shown effectiveness against a range of pathogens, including *Candida albicans, Penicillium notatum, Aspergillus niger*, and *Fusarium oxysporum*, as well as diverse gram-positive and gram-negative bacteria such as *Escherichia coli, Salmonella typhi*, and *Staphylococcus aureus*. The antimicrobial properties of these extracts, oils, polyphenols, and proteins suggest their potential utility in pharmaceutical applications for combating bacterial, viral, and fungal infections.

***Significance*** | Plant-derived antimicrobials offer promising alternatives to combat antibiotic-resistant microbes, with potential applications in pharmaceuticals and food preservation.

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## Introduction

The bacterial population was studied prior to the use of antibiotics, and it was observed that the increase in resistance to antibiotics was directly proportional to their overuse. Initially, neither animals nor humans harbored antibiotic-resistant microorganisms (Hughes & Datta, 1983). Experiments revealed that the primary cause of this resistance was the activation of genes conferring resistance to antibiotics, resulting from specific environmental adaptations (Davies, 1994).

Resistance genes can cluster within a single or movable genetic element, collectively acting as a barrier against a variety of drugs. This multidrug resistance involves several mechanisms. For instance, a single drug-resistance gene can offer resistance to structurally diverse antibiotics, while structurally similar antibiotics may face resistance due to biochemical processes mediated by the same gene. Furthermore, non-antibiotic agents such as organic salts or disinfectants can activate antibiotic resistance genes. A single transposon can provide resistance to multiple drugs, a phenomenon facilitated through gene capture via integrons (Hall & Collis, 1995; Huovinen et al., 1995; Roy, 1995). Some mechanism is shown in Table 1.

Mutations alter the antibiotic-binding sites, rendering the drugs ineffective. For example, both gram-positive and gram-negative bacteria can develop resistance to fluoroquinolones due to mutations that decrease the drugs' binding affinity and effectiveness

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(Martinez et al., 1998). Microorganisms continue to acquire resistance to antibiotics, partly due to genetic adaptability and mutations (Mazel & Davies, 1999).

Several mechanisms enable bacteria and other microorganisms to resist antibiotics, including reduced permeability, active efflux, failure to activate pro-drugs, alteration of drug targets, drug inactivation, bypassing inhibited steps, immunity proteins, drug sequestration, and target amplification. Initially, bacteria were more permeable to antibiotics, but over time, repeated exposure led to resistance through reduced permeability, such as resistance to aminoglycosides. In bacteria with high permeability, resistance can develop through active efflux, exemplified by the expulsion of tetracycline and fluoroquinolones. Some bacteria resist antibiotics by activating immunity proteins, as seen with the resistance to bleomycin through immunity protein activation.

In other cases, microorganisms become resistant by inactivating antibiotics. For example, aminoglycosides, chloramphenicol, and beta-lactams are inactivated due to bacterial resistance. Some antibiotics require activation before their introduction into bacteria, but premature activation can lead to microbial resistance. The genetic basis for these resistance mechanisms lies in mutations and gene acquisition (Mazel & Davies, 1999).

**1.1 Anti-Microbial Components**

Essential oils contain multiple components, with hydrocarbons being the most important. The antimicrobial activity of essential oils is attributed to their various components, such as esters, oxides, ketones, aldehydes, peroxides, alcohols, and oxides (Janssen et al., 1987). Essential oils have been found to reduce bacterial growth, and in some cases, completely inhibit it. The leaves of *Thymus vulgaris* (thyme) and *Mentha* spp. (mint) serve as sources of essential oils, which, when applied against *Staphylococcus aureus*, *Salmonella typhimurium*, and *Vibrio parahaemolyticus*, effectively inhibited their growth (Akthar et al., 2014).

There is a growing urgency for the discovery of modern treatments due to the prevalence of microbial resistance to multidrug therapies and the reduced sensitivity of new strains (Sieradzki et al., 1999). Pharmaceutical companies are increasingly focused on discovering and extracting secondary metabolites. Plants rich in these secondary metabolites, such as *Syzygium aromaticum*, *Allium sativum*, *Cinnamomum verum*, and *Thymus vulgaris*, have demonstrated a wide range of bioactive properties across various fields. These extracts are obtained through different techniques, influenced by multiple factors such as solvent type, pH, temperature, and extraction time (Cowan, 1999).

Several studies have shown that bacteria resistant to antibiotics became vulnerable when exposed to essential oils. These oils increase bacterial membrane permeability, facilitating antibiotic action (Cox et al., 2000). One of the most significant contributors to bacterial antibiotic resistance is biofilm formation, which provides a multilayered defense. Bacterial cells, even those lacking the mechanisms for antibiotic resistance, become more resistant when grown in biofilms. However, when bacteria are removed from biofilms, they regain susceptibility to drugs (Anderl et al., 2000).

Antibiotics face increased resistance from bacteria grown in biofilms. Biofilms enhance bacterial resistance through various mechanisms, such as reducing antibiotic penetration, slowing bacterial growth due to limited nutrient availability, and forming a multi-layered structure that acts as a strong defense against antibiotics (Stewart, 2002).

Medicinal plants have been used for centuries to combat microorganisms. Extracts from plants, such as polyphenols, proteins, and oils, exhibit a broad spectrum of antibacterial activities. In ancient Egypt, herbs were used for mummification to protect against bacteria involved in decomposition (Martin & Ernst, 2003).

Since the dawn of civilization, honey has been recognized for its wound-healing properties. Its antimicrobial activity is attributed to hydrogen peroxide and its high sugar content (Brudzynski, 2006).

In experimental studies with silver, nanoparticles were found to exhibit potent antimicrobial properties across a wide range of materials. Silver is particularly effective against bacterial strains that have shown resistance to multiple antibiotics. In its nanocomposite form, silver is more effective against microbial infections than in its standard crystalline form (Dunn & Edwards-Jones, 2004; Edwards-Jones, 2006).

Probiotics and prebiotics also play an important role in combating infections. Gastrointestinal infections have been treated with probiotics, which are beneficial bacteria for the digestive system. There are many cases where probiotics, even without prebiotics, have been effective against gastrointestinal and postoperative infections (Jeppsson et al., 2011). This is often due to privileged colonization or the synthesis of extracellular components.

Ribosomally synthesized antibiotics are naturally produced peptides that are part of an organism's defense system. For example, the epidermis of *Rana tigrina* contains ribosomal peptide antibiotics, which are used as antimicrobial agents (Edwards-Jones, 2006). The list of such antimicrobial agents are shown in Table 2.

Non-ribosomally synthesized antibiotics are peptides produced primarily by bacteria and are used against microbes. These peptides are further utilized in the production of other antimicrobial drugs that display a broad range of activity against microbial infections (Freire-Moran et al., 2011).

A therapy known as Stalin therapy has been used in Russia to combat microorganisms. This therapy involves the use of lytic phages and comes in two forms: monotherapy and polytherapy, both incorporating bacteriophages. Bacteriophages replicate quickly and efficiently, making this therapy economical and effective against various diseases, particularly those caused by both

drug-sensitive and drug-resistant pathogens. An additional advantage of this therapy is its harmlessness to the host, as it specifically targets bacteria (Loc-Carrillo & Abedon, 2011).

Plants naturally produce a wide range of chemical compounds with remarkable effectiveness. Since the 19th century, nineteen different categories of bioactive constituents have been extracted from plants. Many of these compounds are used as active components in modern medicine and have been foundational in the development of contemporary drugs (Uddin et al., 2011).

**1.2 Antimicrobial Proteins and Peptides**

In recent years, numerous low-molecular-weight proteins and peptides from various plant sources have been identified. These proteins inhibit the growth of microorganisms by enhancing the permeability of fungal membranes and cell walls. The variable binding affinity to chitin, which differs based on molecular weight, provides plants with defense against phytopathogenic fungi (Roberts & Selitrennikoff, 1986; Hejgaard et al., 1992; Terras et al., 1992).

**1.2.1 Antimicrobial Proteins**

Lactoferrin, an iron-binding glycoprotein, deprives bacteria of essential nutrients due to its iron-binding capacity. When bacteria were grown *in vitro* in the presence of lactoferrin and apo-lactoferrin, it was observed that lactoferrin inhibited various bacterial strains, whereas apo-lactoferrin did not inhibit *Escherichia coli* (Arnold & Cole, 1977). Further research showed that lactoferrin exhibited bactericidal activity, even when bound to iron, against *Streptococcus mutans* (Arnold et al., 1981).

However, more advanced studies revealed that the bactericidal effectiveness of lactoferrin diminishes with its iron-binding activity, indicating that iron-independent lactoferrin is more effective against bacteria (Arnold et al., 1980; Kalmar & Arnold, 1988; Yamauchi et al., 1993).

In an experiment involving Rs-AFP and 2S storage albumins extracted from seeds, these proteins were tested for their antifungal activity. The experiment used two growth mediums: one with low ionic strength (SMF-) and another enriched with ions (SMF+), including calcium chloride and potassium chloride. Rs-AFP proteins were tested against 20 different types of fungi.

In the initial experiment without added salts, Rs-AFP2 maintained its antifungal activity, yielding stronger results than Rs-AFP1. Rs-AFP2 continued to inhibit fungi even when salts were added, but at higher protein concentrations. Increasing the concentration enabled Rs-AFP2 to kill 12 of the 20 fungi, while Rs-AFP1 inhibited 5. However, the physiological activity of 2S albumins was disrupted by the cations, and they failed to inhibit any fungal growth in the salt-enriched medium, though they showed significant antifungal activity in the salt-free medium (Terras et al., 1992).

In another experiment, the antifungal activity of Rs-AFP1 was tested against *Fusarium culmorum* and *Trichoderma* spp. alongside proteins like thionin from *Triticum aestivum* and Mj-AMP from *Mirabilis jalapa*. When divalent and monovalent metal ions were added to the growth medium, it was observed that monovalent cations such as KCl negatively impacted 2S albumins, rendering them ineffective against fungal growth. Both Rs-AFP proteins and thionin from wheat maintained their antifungal activity, while Mj-AMP2's efficacy was diminished. Calcium chloride also reduced the antifungal activity of Rs-AFP1, but had no effect on Mj-AMP2 or Rs-AFP2. No antifungal activity was observed from the 2S albumins, highlighting their sensitivity to salt (Terras et al., 1992).

Ace-AMP1 protein is a lipid-binding protein with sequence similarity to plant non-specific lipid transfer proteins (nsLTPs), though it differs structurally and functionally (Roy-Barman et al., 2006). When tested against *Botrytis cinerea*, Ace-AMP1 demonstrated fungicidal activity. Two additional proteins, Ac-AMP1 and Ac-AMP2, extracted from *Amaranthus* seeds, also displayed antimicrobial properties (Broekaert et al., 1992).

Ace-AMP1, extracted from onion seeds, has shown antimicrobial activity. However, its effectiveness is reduced in media containing physiological cations, indicating its sensitivity to these ions. Despite similarities in sequence, Ace-AMP1 differs from nsLTPs in function, particularly because it does not transfer phospholipids like phosphatidylcholine or phosphatidylinositol, but it can transfer other phospholipids between cell organelles. A notable difference is its much higher antimicrobial activity compared to nsLTPs derived from *Triticum aestivum*, *Zea mays*, and *Raphanus sativus*. The fungicidal activity of Ace-AMP1 is affected by varying ionic concentrations, particularly sodium, magnesium, ammonium, and barium ions, whereas calcium ions decrease its activity. In contrast, the fungicidal protein P-purothionin, extracted from *Triticum aestivum*, showed a drastic decrease in activity under calcium ion treatment (De Caleya et al., 1972; Cammue et al., 1992).

In a comparative study, Rs-nsLTP, Ta-nsLTP, and Zm-nsLTP, extracted from *Raphanus sativus*, *Triticum aestivum*, and *Zea mays*, respectively, were tested alongside Ace-AMP1. Ace-AMP1 exhibited high inhibition levels in both low (SMF-) and high (SMF+) ionic strength media, completely restricting fungal growth. Meanwhile, Ta-nsLTP and Zm-nsLTP showed no fungicidal activity in either medium, and Rs-nsLTP only inhibited two out of twelve fungal species in SMF- medium (Cammue et al., 1995).

**1.2.2 Antimicrobial Peptides**

**Defensins** are basic peptides primarily involved in lipid transfer (Kauffmann et al., 1987). The term "defensin" was introduced by Terras and colleagues (Terras et al., 1995). These peptides range from 45 to 54 amino acids, with an average molecular weight of around 5 kDa (Bloch Jr et al., 1998). Many plant defensin-coding genes are found in *Arabidopsis thaliana*, known as PDF genes (Terras et al., 1995). Defensins are highly effective antimicrobial peptides with broad-spectrum activity against viruses, bacteria, and

fungi. Both Gram-positive and Gram-negative bacteria, as well as fungi, are sensitive to defensins (Sugiarto et al., 2004).

Different parts of plants, especially seeds, are rich in defensins, although they are also present in leaves, pods, tubers, fruits, roots, and floral tissues (Broekaert et al., 1997). Two significant antimicrobial proteins in this family are Rs-AFP1 and Rs-AFP2. Another class of cysteine-rich peptides, knottins, contains 35-37 amino acids and is structurally stabilized by three disulfide bonds (Cammue et al., 1992). Like other plant-derived antimicrobial peptides (AMPs), knottins exhibit strong fungicidal and bactericidal activity, but their effectiveness is limited to Gram-positive bacteria, leaving Gram-negative species unaffected.

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**Hevein-like Protein:** Hevein-like proteins are small, cysteine-rich proteins containing 6–10 cysteine residues that form disulfide bridges, providing structural strength. These proteins are capable of binding chitin and are named "Hevein" due to their structural similarity to Hevein found in the rubber tree (*Hevea brasiliensis*) (Gidrol et al., 1994). Other hevein-like proteins and knottin-type proteins have also been isolated from plants.

Among plant-derived antimicrobial peptides (AMPs), thionins were the first to be used experimentally to test pathogenic activity. Thionins are commonly found in seeds, roots, and stems of plants. Like defensins, their molecular weight is around 5 kDa (Cassab, 1998; Selitrennikoff, 2001; Niarchou et al., 2013). Thionins have also been isolated from various plant parts, including the leaves and endosperm of cereals and many other species (Plattner et al., 2015). Jago and Jagox, in 1885, reported the toxic activity of thionins against yeast in wheat flour (Höng et al., 2021). Thionins are basic peptides with sulfur residues and are abundant in the inner plant layers, though trace amounts are also present in outer cells. They kill pathogens by directly disrupting their cell membranes.

In Pakistan, *Moringa oleifera* is cultivated mainly in southern Punjab and is known for its high antimicrobial activity. *Moringa oleifera* belongs to the family Moringaceae, which has only one genus and is widely distributed in tropical and subtropical regions (Nadkarni & Nadkarni, 1976). The plant can grow up to 5 to 10 meters tall (Morton, 1991). Its leaves are rich in calcium, β-carotene, vitamin C, potassium, and protein, and they contain antioxidant compounds such as flavonoids, carotenoids, ascorbic acid, and phenolics, making *Moringa oleifera* an excellent source of antioxidants (Dillard & German, 2000).

*Moringa oleifera* seeds are primarily responsible for the plant's antimicrobial activity (Olsen, 1987). These seeds contain recombinant proteins that can disrupt bacterial cell walls, affecting both Gram-negative and Gram-positive bacteria (Broin et al., 2002). The seeds can also damage microorganisms by disturbing their

plasma membranes, interfering with essential enzymes, or affecting bacterial replication (Sutherland et al., 1990; Silvestro et al., 2000).

Antimicrobial peptides are small, with molecular weights of 2–9 kDa, and are mostly basic. Disulfide bonds between cysteine residues provide structural stability (Lay & Anderson, 2005). Snakins, another group of stable peptides with six disulfide bonds and a high cysteine content, have shown potent activity against pathogen growth in vivo (Harris et al., 2014).

**1.2.3 Antimicrobial Spices**

Spices exhibit a range of biological activities, including anticarcinogenic, antidiabetic, antiviral, analgesic, disinfectant, and anti-inflammatory effects. They have also been shown to preserve food by inhibiting the growth of microorganisms (Curtis et al., 1996). Essential oils in spices are particularly effective against microorganisms. For example, chili pepper extract, capsaicin, controls peripheral nerve pain and inhibits gastric microorganisms (Curtis et al., 1996).

Essential oils extracted from spices such as *Ocimum basilicum*, *Coriandrum sativum*, *Zingiber officinale*, and *Cuminum cyminum* have been reported to inhibit the growth of fungi (*Aspergillus niger*), yeast (*Saccharomyces cerevisiae*), and bacteria (*Mycoderma spp.*) (Meena, 1994). Cinnamon oil also exhibits antifungal activity (Tiwari et al., 1994). Fungal growth, such as *Aspergillus parasiticus*, is inhibited by the fungitoxic effects of oils like eugenol and anethole (Karapinar, 1990). Spices like *Alpinia galanga* and *Curcuma longa* have demonstrated antifungal and antibacterial properties (Elsamma et al., 1996).

The antimicrobial activity of spices from 11 different families has been tested using the agar diffusion method. These spices, including lemon balm (*Lamiaceae*), black pepper (*Piperaceae*), cumin (*Apiaceae*), sweet bay (*Lauraceae*), and chili (*Solanaceae*), showed inhibitory effects against both Gram-positive bacteria (*Bacillus subtilis*, *Staphylococcus epidermidis*, *Staphylococcus aureus*) and Gram-negative bacteria (*Pseudomonas aeruginosa*, *Escherichia coli*). The disc diffusion method also demonstrated that spice extracts inhibit the growth of fungi like *Aspergillus niger* and show antifungal activity against *Candida albicans* (Ertürk, 2006).

**1.2.3.1 *Zingiber officinale***

Ginger, widely used in medicine and cooking, owes its pungent smell and medicinal properties to the volatile oil, gingerol. It helps maintain blood flow and prevents inflammation by inhibiting prostaglandin and leukotriene synthesis (Omoya & Akharaiyi, 2011). *Zingiber officinale*, also known as ginger, is a member of the Zingiberaceae family, which includes other notable spices such as *Curcuma longa*, *Alpinia galanga*, and *Elettaria cardamomum* (Akintobi et al., 2013).

Ginger contains nine compounds that interact with serotonin receptors, offering benefits for gastrointestinal issues and anxiety (Akintobi et al., 2013). Ginger extracts have shown antimicrobial activity. Water extracts have a limited effect, inhibiting the growth of *Staphylococcus aureus* and *Proteus mirabilis*, while ethanol extracts are more potent, inhibiting *Salmonella typhi*, *Pseudomonas aeruginosa*, and *Staphylococcus aureus*. However, bacteria like *Escherichia coli* and *Bacillus subtilis* were resistant to ethanol extracts from *Zingiber officinale* (Akintobi et al., 2013).

**1.4 *Curcuma longa***

*Curcuma longa*, commonly known as turmeric, is valued both as a spice and for its pharmaceutical properties. It is effective in relieving flatus, treating liverache, combating intestinal parasitic worms, and alleviating constipation (Srimal, 1997). Oleoresin, a raw product of turmeric, is used industrially to produce the yellow coloring agent known as curcumin. Even after the isolation of curcumin from oleoresin, it retains bactericidal properties (Negi et al., 1999).

In South Asian countries, including China and India, turmeric is widely used as a condiment, coloring agent, and food preservative. Belonging to the family *Zingiberaceae*, *Curcuma longa* contains important constituents such as sesquiterpenes and curcuminoids in its rhizome. These compounds exhibit various biological activities, including promoting wound recovery (Maheshwari et al., 2006), treating inflammation (Sandur et al., 2007), and demonstrating antimicrobial and anticancer effects (Kim et al., 2012). Extracts from turmeric, including water, aqueous, and methanol extracts, have shown varied effectiveness against bacteria like *Escherichia coli*, *Candida albicans*, *Staphylococcus aureus*, and *Salmonella typhi*. The methanol extract proved most effective, inhibiting growth of all tested bacteria, while water extract inhibited *Salmonella typhi* and *E. coli* (Gul & Bakht, 2015).

**1.5 *Allium cepa***

*Allium cepa*, commonly known as onion, is a biennial herb that can grow up to 1.2 meters in height. It is notable for its nutritional and antimicrobial properties, as well as its anti-inflammatory and antihistamine effects (Organization, 1999; Griffiths et al., 2002). Research has demonstrated that *Allium cepa* exhibits antiparasitic, antibacterial, and fungicidal activities (Elnima et al., 1983; Zohri et al., 1995; Rose et al., 2005; USDA, 2007).

Different extracts of *A. cepa*, including butanol, water, and petroleum ether, were tested against eight microorganisms, including one fungal species and both gram-positive and gram-negative bacteria. Low concentrations of these extracts showed limited effectiveness, while high concentrations completely inhibited bacterial growth. *Candida albicans* displayed resistance to low concentrations of butanol, ethanol, and petroleum ether extracts but was significantly affected by higher concentrations. Chloroform and ethyl acetate extracts exhibited the highest inhibition zones against *C. albicans*. For *Erwinia carotovora*, high concentrations of ethyl acetate extract showed the greatest inhibition, with chloroform and butanol extracts having similar effects. Ethanol extract did not affect bacterial growth, and

**Table 1**. Mechanism of drug resistance by pathogens

| Sr. No. | Antibiotics | Mechanisms by which microbes resist drugs effect |
|---|---|---|
| 1 | Rifampicin<br>Aminoglycosides<br>Chloramphenicol<br>beta-lactams | Drug Inactivation |
| 2 | Aminoglycocides | Reduced permeability |
| 3 | Trimethoprim<br>Sulfonamide | Multiple Targets and their amplification |
| 4 | Bleomycin | Production of resistant protein |
| 5 | Rifampicin<br>Erythromycin<br>Tetracycline<br>Fluoroquinolones | Drug target Variation |
| 6 | Beta-lactams | Blockade of drug |
| 7 | Isoniazid | Pro-drug not activated |

**Table 2.** Plant based antimicrobial agents

| **Antimicrobial agents** | | **Source** | **Nature** | **Active Against** |
|---|---|---|---|---|
| Proteins | Lactoferrin | milk, tears, saliva, vaginal secretions, semen, bronchoalveolar lavage fluid, and specific granules of polymorphonuclear leukocytes(PMNs) | iron-binding glycoprotein | Bacteria Streptococcus mutans |
| | Rs-AFP | Radish seeds | Highly basic oligomeric proteins | Fungi Alternaria longipes |
| | 2S storage | Dandelion seeds | Seed storage proteins | Fungi Phytophthora infestans |
| | albumins | Onion seeds | Lipid transfer protein | Fungi Botrytis cinerea |
| | Ace- AMP1 | M. jalapa | Small, cationic and cysteine-rich antimicrobial peptides | Fungi Cercospora beticola |
| | Mj-AMP | Triticum sativus, Zea mays and Raphanus sativus. | Non-specific lipid transfer proteins | Fungi Alternaria brassicola Ascochyta pisi Botrytis cinerea Fusarium culmorum Verticillium dahliae |
| | nsLTPs | Velvet flower seeds Amaranthus caudatus | Antimicrobial peptides | Candida albicans |
| | Ac-AMP1 | Arabidopsis thaliana | Antimicrobial peptides | Fungi Yeast |
| Peptides | Defensins | Wheat | Plant-specific antimicrobial peptides | Fungi Yeast |
| | Thionins | Zea mays husk | Basic Catalyst | Bacteria E.coli |
| Alcohol | Chromium oxide | Philippine Piper betle L | Anti-bacterial alcohol | Vibrio, Cholerae ogawa, Staphylococcus aureus and Streptococcus pneumoniae |
| Alcohol | Methanol Ethanol | l-arginine | Anti-bacterial oxide | Mycobacteria, and Salmonella |
| Oxides | Nitric oxide | Thyme and Mint | Antibacterial oil extracts | Staphylococcus aureus, Salmomella typhimurium and Vibrio parahaemolyticus |
| Oil extract | Oil from thyme and mint leaves | milk, tears, saliva, vaginal secretions, semen, broncho alveolar lavage fluid, and specific granules of polymorphonuclear leukocytes(PMNs) | iron-binding glycoprotein | Bacteria Streptococcus mutans |

*Escherichia coli* was most strongly inhibited by ethyl acetate extract, with water extract showing minimal effect and chloroform extract showing moderate effectiveness (Bakht et al., 2014).

**1.6 *Syzygium aromaticum***

*Syzygium aromaticum*, known for its clove oil, is used to treat tooth infections and relieve toothache pain. Clove oil can enter the bloodstream through the pulp chamber (Sarrami et al., 2002; Martínez-Herrera et al., 2016). It is also used to treat diarrhea, stomachache, liver diseases, and as a nerve tonic. Clove oil aids in alleviating flatulence and has been used as a remedy for cholera, malaria, and as a preventive measure against tuberculosis.

**1.5 *Syzygium aromaticum***

*Syzygium aromaticum*, commonly known as clove, has been used historically in America for food preservation and to combat food-spoiling microorganisms, including bacteria, viruses, fungi, and worms (Bhowmik et al., 2012). The clove-derived terpenes, known as sesquiterpenes, act as carcino-preventive agents by inhibiting the growth of cancer-causing agents (Miyazawa & Hisama, 2001). Clove oil has applications in various industries, including detergents, fragrances, and automobile cleaning agents (Sarrami et al., 2002).

**Botanical Features of *Syzygium aromaticum***

The hypodermis of *S. aromaticum* contains an oil duct known as a schizolysigenous duct, which houses the essential oil of clove. The calyx features oil glands with thick, rigid sepals. The flower exhibits radial symmetry with an inferior ovary, a shortened style, and sepals, petals, and stamens situated at the top of the hypanthium. The flower is bisexual, with a corolla consisting of four distinct overlapping petals and free stamens covered by the petals, forming the head of the clove bud.

The epidermal layer comprises small linear-walled cells covered by a thick cuticle. The stomata in the epidermis are Ranunculaceous. The cortex has three distinct layers: the outermost layer with enlarged parenchyma cells enriched with large oval-shaped schizolysigenous oil glands; the middle layer containing the vascular bundle; and the innermost layer composed of loosely embedded aerenchyma cells. The columella layer also includes xylem and phloem tissues, with parenchymatous tissues forming the middle cylindrical layer (Holloway et al., 2004). Studies have shown that essential oils contain three main components—eugenol, eugenyl acetate, and caryophyllene—though their concentrations can vary based on factors like pre-extraction treatment, extraction methods, and agroecological conditions (Alma et al., 2007; Santin et al., 2011; Mbaveng & Kuete, 2017).

The flowers of *S. aromaticum* are grouped in clusters and hold commercial value. Bud production typically begins in the fourth year of cultivation. The buds, initially pale, turn green and then red when ready for harvest. Upon drying, they become brown and are known as cloves, used as a spice (Mbaveng & Kuete, 2017). The leaves are glabrous, elongated, and rich in oil glands at their base, while the fruit resembles an olive (Mbaveng & Kuete, 2017).

Different extracts of *S. aromaticum* have shown significant antifungal activity. For example, clove extracts tested using the agar well diffusion method were effective against *Candida albicans* (Mansourian et al., 2014). Methanol extracts demonstrated fungicidal activity against various fungal species, including *Penicillium notatum*, *Aspergillus niger*, and *Fusarium oxysporum*. Additionally, methanolic extracts exhibited inhibitory effects against several bacterial species, such as *Escherichia coli*, *Salmonella typhi*, and *Staphylococcus aureus* (Abd El Azim et al., 2014). Clove oil extracts have also shown bactericidal activities, inhibiting bacterial protein and lipid biosynthesis, and affecting the growth of fungi from both plant and animal sources (Assiri & Hassanien, 2013; Rana et al., 2011).

## Conclusion

This review underscores the significant antimicrobial potential of plant-derived substances. Spices, essential oils, and antimicrobial peptides exhibit remarkable efficacy against resistant microbes, highlighting their value in developing new therapeutic and preservative solutions. Further research and development could enhance their application in combating bacterial, viral, and fungal infections, potentially addressing the growing challenge of antibiotic resistance.

## Author contributions

S.S. led the conceptualization and design of the study. K.H.S. contributed to the analysis and interpretation of the data. T.R. , M.U.K., and M.B.K. were involved in data collection, drafting, and revising the manuscript. All authors reviewed and approved the final version of the manuscript.

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The authors have no conflict of interest.

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