



Exploring the food safety and preservation landscape of *Myristica fragrans* (L.) against foodborne pathogen: A review of current knowledge

Zaryab Shafi^a, Vinay Kumar Pandey^{b,*}, Umme Habiba^c, Rahul Singh^{c,**},
 Mohammad Shahid^d, Sarvesh Rustagi^e, Béla Kovács^{f,***}, Ayaz Mukarram Shaikh^f

^a Department of Biosciences, Integral University, Lucknow, Uttar Pradesh, 226026, India

^b Research & Development Cell, Biotechnology Department, Manav Rachna International Institute of Research and Studies (Deemed to Be University) Faridabad, 121004, Haryana, India

^c Department of Bioengineering, Integral University, Lucknow, Uttar Pradesh, 226026, India

^d ICAR-National Bureau of Agriculturally Important Microorganisms, Maunath Bhanjan, Uttar Pradesh, 275103, India

^e Department of Food Technology, School of Applied and Life Sciences, Uttarakhand University, Dehradun, Uttarakhand, India

^f Faculty of Agriculture, Food Science and Environmental Management, Institute of Food Science, University of Debrecen, Debrecen, 4032, Hungary

ARTICLE INFO

Keywords:

Myristica fragrans
 Natural preservatives
 Antimicrobial activity
 Food shelf life
 Foodborne disease prevention
 Bioactive compounds

ABSTRACT

Foodborne diseases (FBDs) are a severe threat to public health. FBDs are a leading cause of morbidity and mortality, particularly in developing nations with inadequate access to health care and poor sanitation. Pathogens such as *Salmonella*, *Escherichia coli* (*E. coli*), *Listeria monocytogenes*, *Campylobacter*, and *Vibrio cholerae* can cause various illnesses, underscoring the urgent need for global improvements in food safety. Effective strategies are urgently needed to control and prevent such diseases and their causal agents. *Myristica fragrans* (L.) has emerged as a potential natural antimicrobial agent, but its activity against foodborne microbes has been poorly explored. Extracts obtained from *M. fragrans* extend their shelf life and reduce foodborne pathogens. *M. fragrans* holds promise as a natural antimicrobial agent, with implications for improving food safety and preservation, while urging continued research to overcome the existing challenges. To assess the effects of extracts and phytochemicals from *M. fragrans* and their method of action using in vivo models, more thorough research is required. The bioactive compounds found in *M. fragrans*, including myristicin and eugenol, demonstrate strong antimicrobial activity, making them promising candidates for food preservation. This review provides an overview of the antimicrobial properties of *M. fragrans* and its mechanism of action against foodborne bacteria.

1. Introduction

Infection with foodborne pathogens represents a significant threat to global public health because of the consumption of contaminated foods [1]. These diseases result from eating food that contains pathogenic microbes, toxins, and chemical contaminants. Foodborne illnesses are caused by various pathogens, including bacteria (a major source), viruses, parasites, and fungi. Some of these bacterial pathogens include *Salmonella* spp., *Escherichia coli*, *Listeria monocytogenes* and *Staphylococcus aureus* [2]. Chemical preservatives prevail in the context of synthetic antimicrobial agents or antibiotics, which have been traditionally employed to reduce microbial contamination in food. In contrast, the

need to find alternative antimicrobials has become apparent because of concerns over antibiotic resistance, potential health hazards, and consumer demand for minimally processed or natural foods. The utilization of natural antimicrobial compounds sourced from plants, herbs, spices, and other botanical sources is increasing as a viable alternative to synthetic options. The benefits of plant extracts as natural antimicrobials arise from their bioactive compounds, which offer perceived safety, non-toxicity, and the possibility of synergistic action. In addition, several natural antimicrobial agents have a long history of traditional use in medicine and food preservation, which forms an important basis for their study as contemporary food safety approaches [3]. Of the other botanical sources studied for their antimicrobial action, *M. fragrans* also

* Corresponding author.

** Corresponding author.

*** Corresponding author.

E-mail addresses: v.k.pandey30@gmail.com (V.K. Pandey), rahulsingh.jnu@gmail.com (R. Singh), kovacs@agr.unideb.hu (B. Kovács).

Table 1
Studies demonstrating the antimicrobial activity of *M. fragrans* against food-borne bacteria.

Study type	Pathogens Tested	Finding	References
<i>In vitro</i>	<i>Salmonella</i> spp., <i>Escherichia coli</i> , <i>Listeria monocytogenes</i> , <i>Staphylococcus aureus</i>	Significant inhibition of bacterial growth by nutmeg extracts using agar well diffusion assays.	Oo et al. [6]
<i>In vitro</i>	<i>Salmonella enterica</i> serovar Typhi	Nutmeg essential oil demonstrated substantial inhibition of bacterial growth.	Ashokkumar et al. [7]
<i>In vitro</i>	<i>Escherichia coli</i> O157:H7	Potent antibacterial activity of <i>M. fragrans</i> against <i>E. coli</i> O157:H7.	Al-Mariri et al. [8]
<i>In vitro</i>	Foodborne bacterial strains	Effective antimicrobial activity of nutmeg essential oil against various foodborne bacteria.	Al-Mariri et al. [8]
<i>In vitro</i>	<i>Salmonella enterica</i>	Reduction in bacterial colonization and improvement in survival rates in mice infected with <i>Salmonella enterica</i> upon nutmeg extract treatment.	Matulyte et al. [9]
Clinical trial	High-risk population	Significant reduction in the incidence of gastrointestinal infections in high-risk individuals supplemented with nutmeg compared to placebo.	Xu et al. [10]
Chemical analysis	Not applicable	Identification of bioactive compounds such as myristicin, elemicin, and eugenol in nutmeg extracts with significant antimicrobial properties.	Setty et al. [11]
<i>In vitro</i>	Multidrug-resistant <i>Escherichia coli</i> , <i>Staphylococcus aureus</i>	Synergistic antibacterial effects observed between nutmeg extracts and antibiotics against multidrug-resistant bacterial strains.	Khameneh et al. [12]
<i>In vitro</i>	<i>Listeria monocytogenes</i> , <i>Salmonella Typhimurium</i> , <i>Escherichia coli</i> O157:H7	<i>M. fragrans</i> essential oil showed strong inhibitory effects against <i>Listeria monocytogenes</i> and <i>Salmonella Typhimurium</i> , with MIC values of 0.25 µL/mL and 1 µL/mL, respectively.	Sarengaowa et al. [13]
<i>In vitro</i>	<i>Staphylococcus aureus</i> , <i>Escherichia coli</i> , <i>Pseudomonas aeruginosa</i>	Nutmeg essential oil exhibited dose-dependent antimicrobial activity against foodborne pathogens, with MIC values ranging from 0.1 to 1.0 µg/mL.	Ashokkumar et al. [7]
<i>In vitro</i>	<i>Salmonella enterica</i> , <i>Escherichia coli</i> , <i>Listeria monocytogenes</i>	<i>M. fragrans</i> essential oil demonstrated significant antibacterial activity against all tested foodborne pathogens, with MIC values ranging from 0.5 to 1.5 µg/mL.	Kiarsi et al. [14]
<i>In vitro</i>	<i>Escherichia coli</i> , <i>Staphylococcus aureus</i> , <i>Bacillus cereus</i> , <i>Candida albicans</i>	<i>M. fragrans</i> extract exhibited potent antimicrobial activity against Gram-positive bacteria and fungi, with	Ali et al. [15]

Table 1 (continued)

Study type	Pathogens Tested	Finding	References
<i>In vitro</i>	<i>Salmonella Typhimurium</i> , <i>Escherichia coli</i> , <i>Listeria monocytogenes</i>	MIC values ranging from 0.2 to 0.8 mg/mL. Nutmeg oil demonstrated strong antimicrobial activity against all tested pathogens, with MIC values ranging from 0.25 to 1.25 µL/mL.	Li et al. [16]

called nutmeg, is a tropical evergreen tree that belongs to the family Myristicaceae, which is found mainly on the Moluccas or Spice Islands within the Indonesian archipelago. *M. fragrans* has been appreciated for its culinary and medicinal benefits from time immemorial. It yields a pair of the spices: nutmeg, which is derived from the seed and mace that come out of the aril surrounding the seed. Ref. [4]. In addition to its application as a spice and flavoring agent in culinary practices, *M. fragrans* is gaining attention for its putative antioxidant properties, particularly for food safety against microbial and parasitic threats [5]. The bacterial susceptibility of *M. fragrans* is summarized in Table 1, with positive values demonstrating the antagonistic effect of the plant extract on foodborne bacteria.

M. fragrans Houtt. Jaiphal in India, Javitri, and Nutmeg belong to the family Myristicaceae. Lagerstroemia is an evergreen tree that spreads widely, usually ranges from 5 to 13 m in height, and can grow up to 20 m in some instances. The pointed dark green leaves are arranged opposite and opposite to the arrangement, and they are on leaf petioles approximately 1 cm long. The upper leaf surfaces are glossy blooms, and although the flowers are often separated by sex, male and female blooms are present on the tree at the same time. The male flowers blossom in one to ten florets, whereas the female flowers blossom in one to three florets. The flowers are small, white, wax-like, fleshy, and campanulate in shape. The fruit is fleshy, drooping, gold, smooth, borne 6–9 cm in length, and has a longitudinal keel. On maturity, the succulent yellow pericarp breaks open to release two valves, and inside there is a purplish-brown, lustrous seed known as nutmeg surrounded by a scarlet coloured fleshy appendage known as mace. Nutmeg seeds are globular, have a smooth surface, are about 2–3 cm in length when dried, and are roughly oval shaped, hard, and heavy, which is off-white in color with red-brown markings on it. The aril, otherwise called mace, is a bright scarlet when fresh but waxy and shiny, yellowish-brown when dried. It takes the trees about nine years to mature so as to start flowering, but once they start flowering, they will go on to flower for a further 75 years. Usually, trees yield two–three crops per year. The seeds, or nutmegs, take 3–6 weeks to dry to be ready for use [17].

The quality of the contemporary food supply chain is crucial to eliminate foodborne illness outbreaks [1]. The dangers associated with foodborne microorganisms, encompassing various gastrointestinal disorders and their consequences, are significant for consumers. Therefore, there is a great need to develop efficient antimicrobial agents to control these infections to minimize the incidence of foodborne diseases [1]. Antimicrobial drugs can control the growth of potentially hazardous organisms, thereby ensuring the quality and safety of food available to consumers. In the food industry, synthetic antibacterial agents have been used to prolong the shelf life of food and reduce its microbiological load. With regard to natural substances, there is a growing concern regarding the use of natural chemicals in the form of chemicals from plants over the development of antimicrobial resistance and other health impacts of synthetic chemicals. This review aimed to determine whether the natural antibacterial characteristics of *M. fragrans* can be used to enhance food safety. This study will also elucidate the phytochemicals present in *M. fragrans* as well as a brief description of the active fractions in the antibacterial fraction, as well as a comparative analysis of the plant against foodborne infections, all documented in the recent

literature. This review examines the antibacterial properties of *M. fragrans* and their implications for food safety and preservation, focusing on its potential applications in the food industry. This study seeks to elucidate the complete potential of *M. fragrans* in food quality and consumer health by providing a comprehensive evaluation of the current research landscape and suggesting areas for future research.

2. Phytochemical profiling of *M. fragrans*

M. fragrans, commonly known as nutmeg, is a plant with complex phytochemical content that plays a role in modulating its biological activity. The bioactive chemicals found in *M. fragrans* include phenolic compounds, terpenoids, and essential oils, which are the most predominant. These chemicals are mainly found in the seed (nutmeg) and outer skin (mace), which form the core of the spice and are endowed with various flavors and fragrances [18]. Mug worth up to 10 % is constituted of terpene hydrocarbons that include pinene and sabinene, terpene derivatives such as geraniol and linalool, phenylpropanoids including myristicin, elemicin, safrole, eugenol and their derivatives. Among these, myristicin (methoxy-safrole) results in the hallucinatory effect of nutmeg. Scent components in mace oil, which is equivalent to up to 12 % of the spice, also contain terpenoids in lower proportions, although the proportion is approximately 90 % less than that contained in nutmeg butter. Lignans, the diarylpropanoids, are nonvolatile dimers of the phenylpropanoid constituents of essential oils, such as dehydrodiisoeugenol, found in nutmeg and mace with approximately 2 % content. Phenolic compounds, which are known for their antioxidant properties, are abundant in *Myristica fragrans*. Some of these chemicals include flavonoids and phenolic acids. It has been observed that these substances diminish, counteract oxidative stress, annihilate free radicals, and guard cells. It is also an aromatic spice, which means it has a different taste and odor compared to nutmeg, which is mainly due to the content of terpenoids, which include monoterpenes and sesquiterpenes. Additionally, *M. fragrans* contains several highly flammable chemicals with antibacterial and pharmacological effects, including myristicin, elemicin, and safrole. From the above discussion, it can be concluded that these are the unique contributing factors that affect the flavor and aroma of *M. fragrans*: phenolic compounds, Terpenoids, and Essential oils. These chemicals also have diverse biological functions, including antioxidant, bacterial fighter, and pharmacological effects [19].

3. Bioactive compounds of *M. fragrans*

3.1. Myristicin

The organic compound myristicin, which is abundant in plants, such as nutmeg and parsley, has recently been identified as a strong antibacterial agent. Its antimicrobial efficacy is associated with its impact on bacterial membranes. Myristicin is hydrophobic and has an affinity for the lipid portions of bacterial cell membranes. This interaction results in the loss of the membrane structure and stability, thereby enhancing permeability. Myristicin in the intermediate chain affects the lipid bilayer of the membrane, thus creating pores or channels. These pores disrupt the ability of the membrane to act as a barrier for other cellular structures, including ions, proteins, and other molecules. Myristicin has the ability to disarrange bacterial cell membrane permeability, which leads to the disruption of cellular equilibrium. Some of the necessary ions and chemicals that are needed for cell functioning begin to leak out, thus disrupting basic metabolic processes and ultimately leading to cell death. It also affects the bacterial membrane structure and inhibits energy production at the cellular level. It can dissolve the membrane and hence negatively affect the functioning of ATP synthase complexes that are necessary for the survival of bacteria or any other enzymes involved in energy metabolism [20]. Most importantly, it has been established that myristicin is fairly toxic towards microbial cells, provided that it is not very toxic to mammalian cells. This selectivity is due to the chemical

and structural differences between bacterial and mammalian cell membranes, and structures that make bacterial membranes more sensitive to myristicin disruption. The effect of myristicin on bacterial cell membranes causes heightened permeability and diminished integrity, ultimately resulting in cell death during microbial infections. The chemical myristicin is recommended for the development of novel antimicrobial agents against bacteria because of its method of action. Clinical isolates of methicillin-resistant *Staphylococcus aureus* (MRSA) have been shown to exhibit susceptibility to the synergistic antibacterial effects of myristicin and elemicin [21]. The aim of this study was to determine the level of enhanced inhibitory efficacy, and the findings showed that the combined therapy harbored improved efficiency against eight MRSA strains compared to individual treatments. The anti-bacterial and anti-biofilm potential of myristicin encapsulated within nanostructured lipid carriers (NLCs) against *S. aureus* was studied by Ref. [22]. The researchers proved that myristicin possesses remarkable antibacterial effects when administered through NLCs, thus showing its ability to be used as a microbial agent. Ibrahim et al. [4] examined the antibacterial efficacy of myristicin against *S. pneumoniae*. Myristicin significantly inhibits bacterial growth and biofilm formation, indicating its potential utility in managing pneumococcal infections.

3.2. Eugenol

Eugenol has been categorized under phenylpropene, which is a class of chemical molecules comprising a benzene ring with a propene side chain. The chemical structure of this compound is composed of a hydroxy group (-OH) and a methoxy group (-OCH₃), with the latter being a substituent at position three on the benzene ring and the former at position four. Eugenol is present in some parts of *M. fragrans* notably the seed or nutmeg and the aril, which is the red skin surrounding the seed. Eugenol is responsible for the distinctive flavor and scent of both nutmeg and mace, as well as its therapeutic qualities. They are used in culinary practices and, among other applications, in traditional medicine. Eugenol is also credited for the aroma and taste of nutmeg and mace. It has a warm sweet spicy smell akin to that of a clove, but not as strong and sharp. This scent has seen nutmeg becoming widely used in baked products, spice blends, and many savory dishes. Eugenol has been evaluated for its therapeutic effects owing to its many characteristics that have been studied for their potential to promote a healthy body. Dzotam and Kuete [23] observed that eugenol could reduce oxidative stress and free radical generation in the body. The antibacterial properties of eugenol, a bioactive compound found in significant concentrations in *M. fragrans* (nutmeg), have been well investigated and documented. Eugenol has broad-spectrum antibacterial activity against bacteria, fungi, and viruses. It has been proven to suppress the growth of both gram-positive and gram-negative bacteria such as *Staphylococcus aureus*, *Escherichia coli*, *Salmonella* spp., and *Pseudomonas aeruginosa*. Eugenol may help inhibit the cell membrane permeability of microorganisms and cause leakage of cellular content, leading to cell death. Eugenol can interfere with microbial enzymes that are essential for their metabolic processes, energy production, synthesis, and other cellular activities required for their metabolism and survival. The present study further demonstrated that eugenol could increase the formation of reactive oxygen species (ROS) in microbial cells and lead to oxidative stress and cell death. Several studies have shown that eugenol possesses a powerful antifungal effect against many kinds of fungal infections, such as *Candida albicans*, *Aspergillus* spp., and dermatophytes. It can disrupt the lipid layer in fungal cell membranes and hinder the biosynthesis of fungal cell walls, thus preventing fungal development and leading to cell derangement. Compared with the antibacterial and antifungal potential of eugenol, the compound displayed promising antiviral properties against viruses such as herpes simplex virus (HSV) and human immunodeficiency virus (HIV). This may hinder viral replication by blocking viral entry, fusion, and other phases of the viral replication cycle [24]. Eugenol has antimicrobial properties that make it

an appropriate natural preservative for food to enhance its shelf life. Lavender oil has been used extensively in oral health care products such as mouthwash, toothpaste, and dental care products because of its ability to exterminate bacteria and relieve pain. Eugenol is used in pharmaceuticals as an agent for the treatment of various illnesses because of its antibacterial properties, such as topical antifungal solution and oral antiseptic. Eugenol is a antibacterial natural molecule that can be applied in fields such as food preservation, healthcare, and pharmaceuticals [25]. However, more research is necessary to provide a deeper insight into the ways in which nanomaterials work and how they can be effectively applied in several fields.

3.3. Elemicin

One of the main components of nutmeg oil, elemicin, has strong antibacterial and antioxidant properties that are useful for different purposes, including food safety and preservation. Elemicin has also been investigated for its potential to combat different types of bacteria, such as gram-positive (*Staphylococcus aureus*) and gram-negative (*Escherichia coli*) bacteria, owing to its elemicin content (Zhou et al., [26,27]). Elemicin may also interact with the lipid bilayer of bacterial cell membranes, which affects cell fluidity and permeability. This damages the structural capacity of the membrane and cell contents to leak through, finally causing cell death. Like any other macrolide antibiotic, elemicin may interfere with other essential aspects of the bacterial cell, including metabolism and enzymatic processes. Elemicin inhibits certain cellular functions by binding to the active sites of enzymes or interfering with such reactions, thus halting bacterial growth and reproduction [28]. However, elemicin has shown significant antioxidant properties in addition to its bactericidal properties. It scavenges free radicals, which are highly reactive species that the human body's tissues and cells can be adversely affected by oxidative stress. Elemicin promotes general health and well-being by preventing oxidative damage and oxidative stress in cells by scavenging free radicals (Sen and Chakraborty, 2023). Reports have indicated that elemicin can enhance the effects of both myristicin and safrole, which are additional chemicals found in nutmeg oil. These studies revealed that the antibacterial properties of these compounds are enhanced by elemicin when utilized in a mixture [29]. This suggests that both elemicin and other compounds in nutmeg oil may work synergistically to enhance the efficacy of microbial spoilage removal from foods. Therefore, elemicin has many benefits and is a crucial element present in nutmeg oil for various purposes such as food preservation and health enhancement. Its antibacterial activity and synergistic interaction with other phytochemicals, besides its antioxidant effect, are very important to demonstrate the possibility of its use as a natural preservative to increase food shelf life and safety [30].

3.4. Safrole

Safrole, a phenylpropene derivative isolated from nutmeg (*M. fragrans*), demonstrates excellent antibacterial and insecticidal properties that are pivotal for several uses, including food conservation. Safrole is considered to possess strong and broad-spectrum antibacterial activity against a variety of bacterial pathogens of foodborne and environmental origin. Some of its modes of action include the following pathways [31]. Safrole binds directly or indirectly to the phospholipids of bacterial cell membranes, which have a distortive effect on the membranes. This interaction eventually leads to bacterial death, where membranes start to permeabilize and release cellular contents. Furthermore, it has been found that safrole acts on bacterial enzymes by binding to reactive sites or has an impact on other reactions without which bacteria cannot grow and thrive. This inhibition also helps improve its function as an antibacterial agent. Owing to its ability to inhibit the growth of foodborne bacteria, its antimicrobial property will contribute to preventing the deterioration of food. The following foodborne diseases are caused by bacteria that are effective: *Salmonella*, *Escherichia coli* and *Staphylococcus*

aureus as depicted in research. Safrole and other phytochemicals present in nutmeg, such as myristicin and elemicin, have been shown to have an additive effect. The incorporation of safrole in combination with these chemicals has been found to enhance the antibacterial potential of each of these chemicals against a broad spectrum of bacteria. This information shows that it is possible to obtain additional cooperation and coordination in antimicrobial action that can be used in the production of more effective antimicrobial drugs. These include the disruption of bacterial cell membranes and inhibition of enzyme action, which points to the effectiveness of safrole against bacterial diseases [32].

3.5. Phenolic acid

Phenolic acids, such as caffeic and ferulic acids found in this spice, exhibit some functions including antioxidant, anti-inflammatory, and strong anti-bacterial properties against various types of bacteria, including gram-positive and gram-negative bacteria. The mechanisms of action demonstrated efficacy in dealing with microbial-related ailments and overall healthy lifestyles. Phenolic acids affect cell membrane structure; the fluidity and permeability of bacterial cells are affected as a result. This disturbance later leads to cellular content leakage and cell lysis, which in turn slows down bacterial growth and multiplication [33]. The antibacterial properties of ferulic acid and caffeine result from the suppression of bacterial enzymes. The inhibition of bacterial growth is accomplished by binding to active sites and disrupting essential processes such as replication and synthesis, which are crucial for bacterial metabolism [34]. Phenolic acids can induce ROS and reactive oxygen stress in bacterial cells. As pointed out by Juan et al. [35], these ROS negatively impact lipids, proteins, and DNA in cells, thereby affecting bacterial survival and metabolism. Phenolic acids can enhance antimicrobial activity when interacting with other phytochemicals, including flavonoids and essential oils. To increase the general effectiveness of antimicrobial treatments, for example, they can increase vessel permeability, which allows bioactive products to penetrate intracellular bacterial spaces better. Consequently, phenolic acids recycle antioxidant molecules and neutralize free radicals, thereby increasing the antioxidant potential of other phytochemicals. This combination enhances the total capacity of extracts or food matrices to scavenge and protect cells and overall well-being. Moalla et al., Barrie, and Frederickson concluded that phenolic acids enhanced the effectiveness of traditional antibiotics by preventing antimicrobial resistance. They offer a means of supporting the impact of antibiotics in the bacterial biofilm formation process and in general countering antibiotic resistance, since they act independently of one another to hinder the formation of bacterial resistance to multiple antibiotics. Caffeic acid and ferulic acid are examples of phenolic acids that display strong antibacterial effects caused by changes in the oxidation status of the cells, inhibition of vital enzymes, and damage to cell membranes. They interact positively with other phytochemicals by enhancing antioxidant activity, preventing the acquisition of resistance by microorganisms, and enhancing antimicrobial activity. This creates new prospects for use in medicine as well as in food preservation [36].

3.6. Flavonoids

Flavonoids, which are inherent polyphenolic chemicals found in *M. fragrans* nutmeg, include quercetin and kaempferol. Certain phytochemicals, such as flavonoids, are well known to exhibit both antioxidant and antibacterial properties. Because they possess different mechanisms of sub- and synergistic actions, they are important for increasing the safety of food and the stability of food quality. Based on these interactions, flavonoids can change the permeability and structure of bacterial cell membranes. The cellular content thus emerges owing to this disruption and the activities of the bacterial stops, leading to cell death. Quercetin and kaempferol act as antibacterial agents by inhibiting bacterial enzymes. How they work, for instance, by binding to active

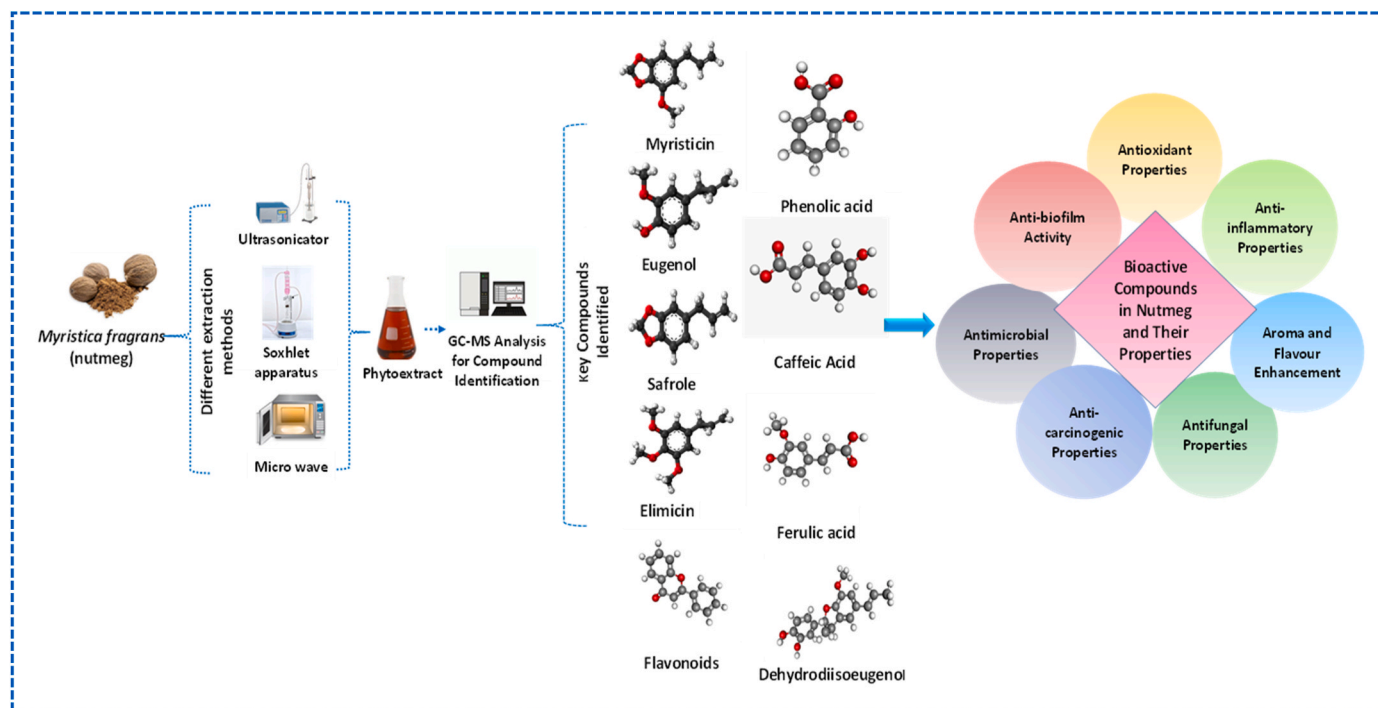


Fig. 1. Phytocompound Present in *M. Fragrans* and it's their properties.

sites or restricting enzymatic processes fundamental for bacterial propagation, arrests bacterial growth and division. Quorum sensing is a bacterial cell-signaling mechanism that is inhibited by flavonoids. This disturbance impairs biofilm formation and diminishes pathogenicity by interfering with cell-to-cell signaling and regulating the expression of related virulence factors. It has also been speculated that flavonoids may have synergistic effects with other phytochemicals, such as phenolic acids or essential oils, and enhance the antibiotic activity. For instance, quercetin and kaempferol enhance the antimicrobial effect of the essential oil by enhancing permeability and allowing bioactive chemicals to penetrate bacterial cells [37]. Therefore, they can be of assistance when administered together with the widely prescribed antibiotics in the battle against Antimicrobial Resistance (AMR). At the molecular level, quercetin and kaempferol enhance the effect of antibiotics in AppKB treatment of multidrug-resistant bacteria through the synergistic mechanisms of growth inhibition and efflux pump modulation. Flavonoids are natural preservatives that enhance hygiene and food conservation. Owing to their ability to curb foodborne bacteria, including *Salmonella* and *Escherichia coli*, they are ideal food preservatives that enhance the quality of food and reduce the incidence of foodborne diseases [38]. The flavonoids that exist in energy drinks include quercetin and kaempferol, which exhibit antibacterial activity via different mechanisms, including membrane disruption, enzyme inhibition, and modulation of cell signaling pathways. Combined with other phytochemicals, they enhance the antimicrobial effect and have a positive effect on combating antimicrobial resistance, which in turn improves food safety and quality [39]. Fig. 1 shows the phytochemicals present in *M. fragrans*. Table 2 lists various mechanisms of action against foodborne pathogens.

4. Characteristic Features of *M. fragrans* in the food industry

M. fragrans, commonly known as nutmeg, is a versatile spice that has been used for centuries in the food industry because of its distinctive flavor, fragrance, and possible health advantages [45]. In this in-depth examination, we will examine the unique capabilities of nutmeg in the food sector, including flavor improvement, aroma and fragrance,

preservation properties, digestive aid potential, anti-inflammatory benefits, and nutritional richness.

4.1. Flavor enhancement

Nutmeg is the seed of *M. fragrans* which has been used since time immemorial for its ability to enhance the taste of food products to the highest level. It is delicate, toasty, sweet, and contains nuts and spice notes, making it a versatile ingredient suitable for sweet and savory dishes. Some of the functionalities include nutmeg, which has the ability to provide warmth and sweetness to meals, which is characteristic of a flavor enhancer. This is because the warm resonant associations of nutmeg connect the spice with coziness and indulgence, much in the same way as cinnamon; for instance, it lends itself well to a number of recipes. Whether used to garnish a freshly brewed cappuccino incorporated into cookies that have just been baked from scratch or to garnish a bowl of the oatmeal, nutmeg gives added a warmer feel to foods that elicit satisfaction with the taste buds. Moreover, nutmeg has a slightly sweet taste that blends well and brings out the natural flavors of other foods, especially dairy, chocolates, and fruits. It enhances creamy texture when used with milk or contributes a velvety ester when combined with chocolates, a sweet undertaste. Likewise, when used in connection with fruit-containing sweets or sauces, nutmeg heightens the fruity sweetness to levels of gourmet endorsement. Apart from enhancing warmth and natural sweetness, nutmeg provides a typical nutty and spicy note and amplifies the flavor of food. Because Nutmeg smells and tastes like roasted nuts, such as almonds or hazelnuts, and has a delightfully savory finish, it adds depth to the dishes. This nuttiness is versatile in pairing with almost any component of root vegetables that are closer to the ground to meat that is richer in terms of texture and flavor to the meal that contributes an elevated attribute to the same.

Furthermore, the very slight note of the spice there is in nutmeg is an awakening to the senses without actually overwhelming them. Nutmeg is a mildly flavored spice that enhances meals, but its intensity is not as high as that of spices such as chilli powder and cayenne pepper. Whether added to a rich soup, poured over a dish of savory sauce, or mixed into a marinade for grilled meats, the mildly spicy flavor of nutmeg elevates

Table 2
Mechanistic approach of *Myristica fragrans* Phytochemicals against Foodborne Pathogens.

Phytochemical	Mechanism of Action	Significance	Example	References
Myristicin	- Disruption of bacterial cell membranes - Inhibition of enzyme activity	Myristicin, abundant in nutmeg, exhibits potent antimicrobial activity against various foodborne pathogens, including <i>Salmonella</i> , <i>E. coli</i> , and <i>S. aureus</i> . It contributes significantly to food safety and preservation.	Myristicin from nutmeg oil effectively inhibited the growth of <i>Salmonella</i> and <i>E. coli</i> at low concentrations.	[40]
Elemicin	- Disruption of bacterial cell membranes - Inhibition of enzyme activity	Elemicin, a major constituent of nutmeg oil, displays antimicrobial properties effective against a wide range of foodborne pathogens, thereby enhancing food safety and extending shelf life.	Elemicin extracted from nutmeg oil showed strong inhibitory effects against <i>S. aureus</i> and <i>L. monocytogenes</i> .	[24]
Safrole	- Disruption of bacterial cell membranes - Inhibition of enzyme activity	Safrole, found in nutmeg oil, exerts antimicrobial effects against foodborne pathogens such as <i>L. monocytogenes</i> , <i>B. cereus</i> , and <i>C. jejuni</i> , contributing to food preservation and safety.	Safrole extracted from nutmeg oil demonstrated significant antibacterial activity against <i>L. monocytogenes</i> , reducing bacterial growth by over 90 %	[14]
Phenolic Compounds Caffeic Acid, Ferulic Acid	- Disruption of bacterial cell membranes - Inhibition of enzyme activity - Antioxidant properties	Phenolic compounds present in nutmeg, such as caffeic acid and ferulic acid, exhibit robust antimicrobial activity against a broad spectrum of foodborne pathogens, while also providing antioxidant protection against oxidative stress.	Caffeic acid and ferulic acid extracted from nutmeg demonstrated strong antimicrobial activity against <i>E. coli</i> and <i>S. aureus</i> , with minimal inhibitory concentrations (MICs) below 100 µg/mL.	[41]
Flavonoids Quercetin, Kaempferol	- Disruption of bacterial cell membranes - Inhibition of enzyme activity - Modulation of cell signalling pathways	Flavonoids found in nutmeg, including quercetin and kaempferol, possess potent antimicrobial effects against common foodborne pathogens like <i>C. perfringens</i> , <i>V. parahaemolyticus</i> , and <i>L. monocytogenes</i> . Their multifaceted mechanisms contribute to improved food safety and quality.	Quercetin and kaempferol isolated from nutmeg demonstrated significant antimicrobial activity against <i>C. perfringens</i> , inhibiting bacterial growth by over 80 % at concentrations of 50 µg/mL	[42]
Lignans Trimyristin, Dehydrodiisoeugenol	- Inhibition of bacterial growth - Disruption of biofilm formation	Lignans, such as trimyristin and dehydrodiisoeugenol, present in nutmeg, exhibit antimicrobial properties by inhibiting bacterial growth and disrupting biofilm formation. This aids in preventing food spoilage and reducing the risk of foodborne illnesses.	Trimyristin extracted from nutmeg showed potent inhibitory effects against biofilm formation by <i>E. coli</i> , reducing biofilm biomass by 75 % at a concentration of 200 µg/mL	[43]
Terpenes α-Pinene, β-Pinene	- Disruption of bacterial cell membranes - Inhibition of enzyme activity - Modulation of cell signalling pathways	Terpenes present in nutmeg, such as α-pinene and β-pinene, possess antimicrobial effects against foodborne pathogens due to their ability to disrupt cell membranes and interfere with bacterial metabolism.	α-pinene isolated from nutmeg exhibited strong antibacterial activity against <i>B. cereus</i> , inhibiting bacterial growth by 90 % at a concentration of 100 µg/mL	[44]

the dish and has a lasting impact on those who consume it. The ability of nutmeg to improve flavor is evidence of both its culinary appeal and flexibility. A variety of recipes are elevated to new levels of flavor complexity due to their multifaceted taste, which is a result of their warm, somewhat sweet tones combined with traces of nuttiness and spice. Nutty flavors can be produced in both savory and sweet dishes, which is why nutmeg is a staple in the culinary world. Home cooks and chefs alike adore it for its capacity to elevate simple recipes to extraordinary culinary works of art [46].

4.2. Aroma and fragrance

In addition to its culinary uses, nutmeg is fascinating because of its fragrance, which attracts everybody's senses and warms the atmosphere. The simple fact that nutmeg has a rather strong and distinct smell that can be easily recognized worldwide is one of its key assets as it helps improve the culinary experience while at the same time reminding people of home-cooked meals and happiness. The pungent smell, especially in the newly prepared fresh nutmeg or that which has been ground into a power form, makes it regarded as having a good smell. It is tasty and aromatic; it is flavored as it contains spices. Nutmeg contains many volatile oils, including safrole, eugenol, and myristicin, all of which together play this aromatic composition. These ingredients are responsible for the specific scent of nutmeg, which enhances the collisions of

the space with the scents of spice, warmth, and tender sweetness. Ease beside a kitchen sink, in front of dishes that lay covered, awaiting presentation; the excitement and creativity that culinary artworks bring in early morning cooking times are captured by the nutmeg aroma. It evokes feelings of warmth and recollection and takes them to a place with which they are comfortable and need not fancy. This spice enhances the sense of taste to extremes, making every meal an artwork of delight and taste through baking, cooking, or simple garnishing.

The aroma of nutmeg is particularly fascinating because it has a faint similarity to that of cloves, another popular spice with a warm, spicy perfume. Although nutmeg and cloves both include fragrant chemicals such as eugenol, nutmeg has a unique personality with small differences. This difference gives the scent of nutmeg more depth and complexity, giving it a genuinely exceptional degree of olfactory sophistication. Additionally, the perfume of nutmeg transforms food preparations by adding depth and nuances of flavor that entice the palate and please the senses. The fragrant presence of nutmeg lends a touch of refinement and elegance to both savory and sweet foods, taking even the most basic recipes to new culinary heights [19]. Nutmeg's fragrant appeal is evidence of its culinary skills and timeless appeal. Its rich, aromatic aroma, which evokes memories of warm kitchens and joyous occasions, lends finesse, depth, and coziness to culinary creations. The scent of nutmeg is a delightful addition to food preparation, and a source of comfort, joy, and nostalgia. It can be used as a spice, garnish, or even fragrant garnish.

4.3. Preservative properties

For centuries, it has been known that nutmeg has properties that make food more tardy in spoiling. It is very useful in the preservation of food because it hinders the development of germs and fungi on food surfaces. It is not surprising that such an ingredient possesses antibacterial action because of the presence of myristicin and elemicin in nutmeg. One of the preservation effects of nutmeg is its effect on extending the shelf life of food products. Nutrition/Taste: Manufacturers may assist in maintaining longer shelf life of their goods or food items by including nutmeg in the list of ingredients; thus, this aids in less spoiling of food or products, which in turn reduces wastage. This is particularly important for maintaining the quality of perishable foods such as cheeses, meats, and pickles for a long time. Some constituents found in nutmegs are effective in inhibiting bacterial and fungal formation, which leads to food spoiling. Myristicin, which is one of its primary constituents, has shown intense antibacterial properties against microbes [47].

The second chemical component, elemicin of nutmeg, has bacteriostatic properties that help increase the preserving effects of the spices. Moreover, it has been a few decades since the preservation of talent in traditional food preservation techniques has benefited from the use of nutmeg. Whole nutmeg seeds were crushed or grated and added to meats in a number of cultures before the meat was dried or smoked which was as much to do with preserving the meat as with enhancing the flavor. Besides prolonging the shelf life of meats, this method of preservation gives the meat the taste and smell of nutmeg, thus enhancing the taste and bouquet of the finished meat products. Nutmeg has also been employed to preserve items such as cheese, pickles, baked products, meats, and other items. Because its activity inhibits the development of spoiling organisms, its use has the effect of preserving perishable foods and the shelf life of such products. The ability of nutmeg to preserve food has made it an invaluable tool in the battle against food spoilage, preserving the quality and freshness of various culinary creations. Nutmeg has a well-earned place in the culinary world as both a spice and preservative because of its capacity to suppress microbial development, whether it is utilized in conventional preservation methods or integrated into contemporary food items (Malik et al., 2022).

4.4. Digestive aid

It is conventional wisdom that nutmeg has potential benefits with regard to the functioning of the digestive system and has been used as part of the Ayurvedic system of medicine. Because of its perceived positive qualities in digestion, nutmeg is a common ingredient used in herbal teas and cures, during which it facilitates and speeds up the digestion process, reduces and relieves stomach aches, and generally supports the digestive system. One of the principal digestive functions, nutmeg, has carminative effects. Carminatives contribute to the process of eliminating intestinal gases and, therefore, reduce their formation and occasional discomfort, thus contributing greatly to digestive comfort [48]. Two chemicals in nutmeg, myristicin and eugenol, make it a carminative that is useful in the treatment of diarrhea and other gastrointestinal disorders, such as stomach aches and bloating. The carminative actions of nutmeg, such as gas, pain, or bloating, are particularly beneficial in cases of discomfort after eating. Nutmeg alleviates these symptoms and provides comfort to the digestive system by facilitating the expulsion of intestinal gases. Also, nutmeg is well known saying that it is very stomachic thus pointing towards the probable fact that nutmeg consumption helps strengthen the stomach lining and reduce the chances of having conditions such as Gastritis and Ulcers. It is believed to be beneficial to the health of the stomach owing to its anti-inflammatory properties that reduce inflammation and gastro-protective properties that protect the mucosa of the stomach lining. The spice also has applications in different natural medicine systems,

including the Ayurvedic system, for the management of ailments with symptoms such as heartburn, nausea, and indigestion. It is believed to promote the health of the gastrointestinal tract by stimulating peristalsis and the release of enzymes in the gut, facilitating digestion and assimilation of nutrients into the body [49]. However, the usefulness of nutmeg for digestion does not end with its use as a remedy for extreme stomach pain. Normal digestion and nutrient absorption can be supported by the regular intake of the product, indicating that the periodic use of nutmeg might not have serious negative effects on the body. Nutmeg enhances overall health and energy by supporting digestive wellness, which makes people feel more at ease and satisfied after eating. Owing to its digestive qualities, such as its carminative and stomachic actions, nutmeg is a great ally for enhancing digestive comfort and gastrointestinal health. Nutmeg is a rightful position among natural digestive aid because of its capacity to ease digestive pain and support a healthy digestive system, whether it is used in herbal teas, traditional medicines, or culinary creations [48].

4.5. Anti-inflammatory effects

Not limited to cooking purposes, nutmeg has been credited with some properties of its possible anti-inflammatory factors, which make it a valid method for enhancing health, as well as combatting several chronic inflammatory diseases. Recent studies have focused on the anti-inflammatory potential of nutmeg, which can be attributed to its rich source of bioactive constituents such as myristicin and eugenol. Myristicin and eugenol are two major constituents of nutmeg that have attracted interest in experimental studies because of their anti-inflammatory effects. Among them, C juveniles have established the capability to modify several inflammatory processes in the body by decreasing pro-inflammatory species, thus easing inflammation. Inflammation is a complex biological process that is of tremendous significance in the immunological response of the body to damage or infection. Although acute inflammation is necessary and beneficial for curing and protecting against diseases, chronic inflammation leads to several diseases, such as cardiovascular diseases, diabetes, arthritis, and neurological disorders [50]. In addition, new findings suggest that nutmeg has anti-inflammatory effects that may help patients with inflammatory conditions in the absence of chronic diseases. For instance, evidence showing the anti-inflammatory properties of nutmeg may assist in managing the symptoms of certain diseases, including arthritis, pain, swelling, and stiffness, thus improving the quality of life and dexterity. Although the first index data advocates the therapeutic potential of nutmeg as an anti-inflammatory agent, there is a need to uncover the bureaucades by which this benefit occurs and explore the therapeutic applications of nutmeg extensively. It is also important to determine whether nutmeg plays any role in the bigger scheme of things, as far as the nutrition and physiological well-being of the human body is concerned. However, introducing nutmeg into one's diet may have beneficial effects on health, and this could not be enough to eradicate the effects of constant inflammation. Nutmeg should therefore be seen as one part but not an exhaustive solution for health improvement, which requires people to take meals from healthy sources, exercise, and manage stress, and avoid vices such as smoking and excessive alcohol intake. Myristicin and eugenol, two chemicals in nutmeg that are thought to have anti-inflammatory properties, may have great potential for promoting health and preventing chronic inflammatory diseases [51].

4.6. Rich in nutrients

The nutritional value of nutmeg is extremely high, given that a single dose is as small as a nut. Most commonly, it is employed in limited quantities as a seasoning to enhance the taste and aroma of foods. Incorporating it into a balanced diet, the value of adding nutmeg to the diet arises from the numerous health benefits associated with its nutrient

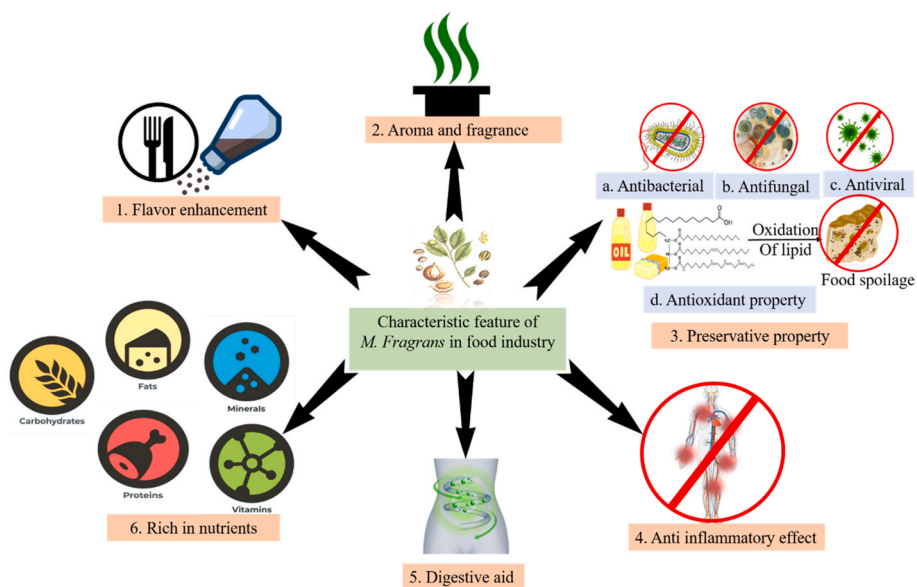


Fig. 2. Characteristic Features of *M. fragrans* in the food industry.

content, such as vitamins, minerals, and antioxidants. For these qualities, the nutritive value of nutmeg is highly desirable and it is rich in vitamins and minerals, which are vital and fundamental nutrients for proper well-being and energy. Vitamin A is a fat-soluble vitamin that is essential for the maintenance of eyesight, enhancing the immune system, and improving the overall health of the skin. This vitamin can be found in large amounts in the nutmeg. In addition, vitamin A plays a role in supporting growth and development in young infants.

Vitamin C, a crucial water-soluble antioxidant and collagen biosynthesis and well-known wound healer, together with being an immunomodulatory agent, is found in nutmeg. Vitamin C also has excellent antioxidant properties that help eliminate free radicals that harm cells. However, there are many small benefits to consuming it; in addition, nutmeg has useful minerals such as calcium, magnesium, and potassium, all of which are needed by the body to perform various functions. Although magnesium is good for nerve conduction, muscular relaxation, energy metabolism, and conduction, calcium helps in building strong bones and muscle contractions. Potassium is helpful in regulating blood pressure, heartbeat, and fluid levels. The antioxidant content of Nutmeg fortifies its nutritional value by extending protection against inflammation and oxidative stress [52]. These antioxidants help in cognitive function, heart function, and healthy aging because they reduce oxidative stress. Moreover, nutrients with high antioxidant levels in nutmeg are associated with other benefits, including anti-inflammatory and protective effects against chronic diseases, including diabetes, heart disease, and some types of cancer. The intake of dietary foods rich in nutmeg is a very effective traditional and modern way of ensuring a

balanced diet and a positive impact on the life of an individual. Nutmeg provides depth of flavor and nutritional value to meals, whether it is used in savory or sweet recipes because of its high nutritional content. However, because nutmeg has a high concentration of certain components, it is vital to consume it in moderation, as excessive intake may have negative consequences. The nutritional advantages of nutmeg go well beyond its use as a flavoring agent. Nutmeg has several health-promoting qualities that boost immune system function, bone health, cardiovascular health, etc. It contains vitamins, minerals, and antioxidants. People may take advantage of the unique flavor and aroma of nutmeg as well as its nutritional richness by including it in a varied and well-balanced diet [53]. The characteristics of *M. fragrans* in the food industry are shown in Fig. 2.

5. Mechanistic action of *M. fragrans* against foodborne bacterial pathogens

This section explores the distinctive antimicrobial actions of *M. fragrans* and highlights its potential for food safety. Unlike traditional studies of natural antimicrobial agents, this review focuses on the diverse bioactive components of *M. fragrans*, such as myristicin, eugenol, and elemicin, and their targeted actions on bacterial pathogens.

5.1. Cell membrane disruption: a targeted mechanism

The cell membrane disruption mechanism of *M. fragrans* compounds, particularly myristicin and elemicin, occurs through a unique lipophilic action that allows these phytochemicals to be embedded within bacterial cell membranes. This integration destabilizes the membrane by altering the lipid structure and fluidity, leading to pores and lesions that increase permeability and cause essential ions, metabolites, and cellular contents to leak out [54]. Recent studies have shown that this targeted disruption prompts rapid cell lysis in bacterial cells, a mechanism supported by findings on the ability of myristicin to quickly destabilize bacterial integrity through structural rearrangements. Additionally, *M. fragrans* compounds promote the production of reactive oxygen species (ROS), further damaging membrane lipids and proteins through oxidative stress. This dual mechanism of physical disruption and ROS induction makes *M. fragrans* especially lethal to bacterial cells, setting it apart from general antimicrobials that require internal cell penetration for efficacy [55].

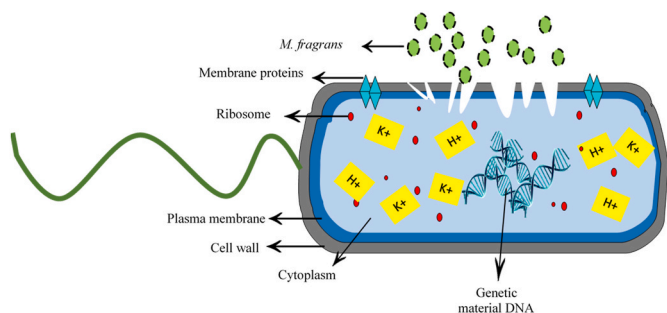


Fig. 3. Illustration depicting the mechanistic action of *Myristica fragrans* (Jai-phal) against foodborne bacterial pathogens.

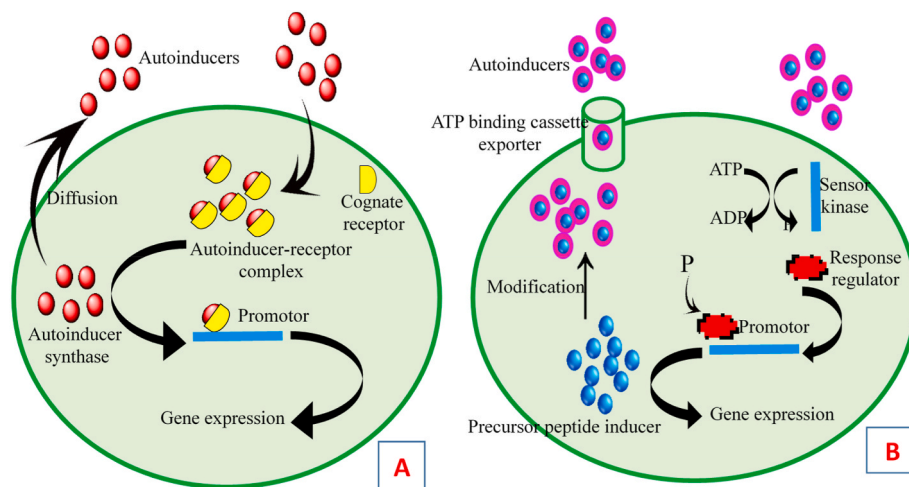


Fig. 4. Role of *M. fragrans* (L.) as a natural antimicrobial agent against foodborne bacteria.

Unlike conventional antimicrobials that rely on intracellular targeting, *M. fragrans* uniquely affects the external structure of the cell, allowing it to evade bacterial defenses that often prevent antimicrobial entry. This characteristic, combined with its specific interaction with lipid molecules, minimizes the likelihood of rapid bacterial resistance. Cruz et al. [56] highlighted the potent bactericidal activity of *M. fragrans* compounds against foodborne pathogens, such as *Escherichia coli* and *Listeria monocytogenes* at minimal inhibitory concentrations. These findings indicate that *M. fragrans* is a promising natural preservative for food safety, offering broad-spectrum efficacy, resistance to adaptation, and alignment with the consumer demand for natural additives. This review identifies *M. fragrans* as a novel clean-label solution that enhances food preservation through its multifaceted targeted antimicrobial actions. Fig. 3 schematically shows the cell wall disruption mechanism.

5.2. Enzymatic inhibition

The inhibition of key bacterial enzymes by *M. fragrans* compounds is a unique and highly effective antimicrobial mechanism. The primary bioactive constituents—myristicin, elemicin, and eugenol—have been shown to interfere with enzymes essential for bacterial metabolism and cellular processes, thereby exerting bactericidal or bacteriostatic effects [6]. These enzymes are crucial for cell wall formation, DNA replication, and protein synthesis, and are integral to bacterial growth and survival. By targeting specific active sites on these enzymes, *M. fragrans* compounds can hinder enzyme catalysis, either reversibly or irreversibly, based on their chemical properties or binding capabilities. This prevents substrates from accessing enzyme active sites, freezes enzyme activity, or alters enzyme structure, rendering the enzymes nonfunctional. More specifically, *M. fragrans* compounds may inhibit cell wall-synthesizing enzymes, similar to penicillin-binding proteins (PBPs), thereby weakening the bacterial cell wall and leading to cell lysis. Additionally, compounds such as myristicin interfere with DNA-processing enzymes such as DNA gyrase and topoisomerase, which are crucial for DNA unwinding and replication. This interference results in the accumulation of DNA damage, ultimately causing bacterial cell death. Similarly, certain phytochemicals from *M. fragrans* can inhibit ribosomal function and aminoacyl-tRNA synthetases, impeding protein synthesis and resulting in the formation of defective proteins that are lethal to bacterial cells [57]. Beyond these primary mechanisms, *M. fragrans* compounds also affect enzymes critical to metabolic pathways, such as glycolysis, the TCA cycle, and fatty acid synthesis, leading to disrupted energy production and biosynthesis. Notably, when used in conjunction with other antimicrobials, *M. fragrans* phytochemicals have demonstrated

synergistic effects that enhance antimicrobial efficacy and help overcome antibiotic resistance, making them valuable for combating resistant bacterial strains [58]. This combination of targeted enzyme inhibition and synergistic potential uniquely positions *M. fragrans* as a promising natural antimicrobial agent with broad-spectrum applications for food safety and preservation.

5.3. Quorum sensing (QS) inhibition and biofilm disruption

Bioactive compounds in *M. fragrans* target quorum sensing (QS) pathways and biofilm formation, which are key bacterial processes that contribute to pathogenicity and antibiotic resistance. QS is a gene regulation mechanism used by bacteria to coordinate behavior, including biofilm formation, based on population density. *M. fragrans* compounds effectively interfere with bacterial communication by inhibiting QS signals, thereby limiting biofilm development and reducing virulence [59]. Specifically, *M. fragrans* compounds target acyl-homoserine lactones (AHLs) in gram-negative bacteria, and auto-inducing peptides (AIPs) in gram-positive bacteria. This disruption of QS signaling pathways and regulatory systems like LuxR/LuxI (Gram-negative) and Agr (Gram-positive) downregulates genes associated with virulence factors, including haemolysins, proteases, exotoxins, and biofilm-associated proteins (Zhou et al., [26,27]).

Beyond QS inhibition, *M. fragrans* compounds prevent bacterial cells from adhering, congregating, and forming mature biofilms by interfering with extracellular polymeric substance (EPS) components, such as polysaccharides, proteins, and extracellular DNA. This interference compromises biofilm stability and structural integrity, leaving bacterial cells more vulnerable to antimicrobial agents and immune defense. Moreover, *M. fragrans* compounds can promote the dispersal of pre-existing biofilms, detach bacterial cells from the protective matrix, and enhance the effectiveness of conventional antibiotics [60]. Through QS disruption, inhibition of biofilm maturation, and biofilm dispersion, *M. fragrans* acts as a potent natural agent against biofilm-associated bacterial infections, positioning it as a valuable adjunct to antimicrobial therapy and a promising candidate for natural food preservation. Fig. 4 shows the role of *M. fragrans* (L.) as a natural antimicrobial agent against foodborne bacteria.

6. Application of *Myristica fragrans* in food preservation

M. fragrans extracts or essential oils obtained through methods such as steam distillation or solvent extraction [61], can be effectively integrated into various food products. An optimal formulation requires careful selection of carriers, solvents, and emulsifiers to ensure

compatibility and stability of the extract within the food matrix. Adjusting the incorporation level of *M. fragrans* extracts or essential oils helps achieve the desired antimicrobial effect without compromising sensory qualities, with minimum inhibitory concentrations (MIC) against foodborne pathogens such as *E. coli* and *Salmonella* typically observed in the range of 0.2–0.8 mg/mL, depending on the food matrix [62]. For stability and controlled release, *M. fragrans* compounds may be microencapsulated, which protects bioactive elements from degradation and ensures uniform dispersion throughout the product [63]. Microencapsulation has been shown to maintain efficacy by slowly releasing active compounds, thereby extending the antimicrobial action over time. For instance, in meat products, studies such as that by Sarıcaoglu and Turhan [64] have reported a significant shelf-life extension of up to 50 % when nutmeg essential oil was used to prevent spoilage bacteria, demonstrating a reduction in bacterial counts by 1.5–2.0 log CFU/g after 7 days of storage. *M. fragrans* compounds act through several diverse pathways to protect food products from microbial contamination. Lipophilic components such as myristicin and elemicin integrate into bacterial cell membranes, destabilize them, and result in increased permeability. This leads to cell lysis and controlled microbial death, as evidenced by reductions in bacterial populations by 2–3 log CFU/g in dairy and meat samples treated with *M. fragrans* [65]. *M. fragrans* compounds inhibit enzymes that are essential for microbial growth, such as those involved in cell wall synthesis and metabolic pathways. This disruption arrests bacterial growth, contributing to a further 30–40 % reduction in spoilage rates. By disrupting bacterial quorum sensing pathways, *M. fragrans* inhibits biofilm formation, which plays a key role in bacterial resistance. This effect is particularly beneficial for processed foods where biofilm-associated pathogens are a significant concern. Studies have shown that biofilm formation can be reduced by up to 60 % in treated samples, helping to maintain food quality over extended storage periods (Zhou et al., [26,27]). To ensure consumer safety, food items containing *M. fragrans* must adhere to regulatory guidelines, including proper processing, labeling, and quantification of antimicrobial levels. The integration of *M. fragrans* extracts or essential oils into food matrices provides an effective and natural alternative for enhancing food preservation while maintaining food safety and quality.

6.1. Indirect use in food packaging as an additive

Recent research has underscored the possibility of integrating *M. fragrans* essential oils into food packaging materials, offering a unique method for food preservation. These essential oils, which are abundant in bioactive components, such as eugenol, demonstrate potent antibacterial, antifungal, and antioxidant capabilities that successfully suppress the proliferation of spoilage microorganisms and foodborne pathogens, thus preserving food quality [66]. The integration of these bioactive compounds into packaging materials offers a cutting-edge solution to extend the shelf life of perishable foods without relying on harmful chemical preservatives.

When infused into packaging materials, *M. fragrans* essential oils create a dynamic antimicrobial environment that gradually releases these protective agents over time. This controlled release mechanism ensures continuous protection, reducing microbial contamination and spoilage, while maintaining the sensory integrity of the food, such as its flavor, texture, and appearance [67]. This innovative packaging method is especially beneficial for highly perishable products, such as fresh produce, meat, and dairy, which are particularly vulnerable to microbial growth.

What makes *M. fragrans* essential oils even more appealing is their natural origin, which provides an eco-friendly and sustainable alternative to synthetic additives. As consumers increasingly demand natural, safe, and environmentally conscious products, packaging infused with these essential oils has responded to this trend, offering a green solution for food preservation [68]. The antimicrobial properties of *M. fragrans* not only enhance food safety, but also reduce the need for artificial

preservatives, aligning with the global movement toward clean-label products.

In addition to extending the shelf life, the incorporation of *M. fragrans* essential oils into biodegradable packaging materials enhances sustainability, addressing both food waste and environmental concerns. Studies have demonstrated the successful infusion of essential oils into various packaging materials such as films, coatings, and containers, many of which are derived from renewable sources [69]. This combination of functionality and sustainability offers a promising approach to revolutionizing the food packaging industry, providing a viable solution for food preservation and waste reduction. As research continues to explore the optimal concentrations, release dynamics, and compatibility of *M. fragrans* essential oils with various food products, the future of food packaging is expected to embrace this innovative, natural preservative technology, paving the way for safer, longer-lasting, and more sustainable food packaging solutions [70].

6.2. Effects on shelf-life extension and reduction of foodborne pathogens

M. fragrans exhibits potent antimicrobial effects against a broad spectrum of foodborne pathogens, including bacteria and fungi (Arumugam et al., 2019). When integrated into food matrices, *M. fragrans* compounds inhibit microbial growth, significantly reducing spoilage rates, and extending the shelf life of various products. For example, Xedzro et al. [65] demonstrated that the application of nutmeg extracts in dairy products, specifically milk, reduced bacterial counts by up to 2 log CFU/mL, thereby improving microbiological quality and extending shelf life by approximately 50 % compared with untreated samples.

M. fragrans compounds inhibit key bacterial enzymes critical for cell wall synthesis and DNA replication, thereby arresting microbial growth. Cruz et al. [71] demonstrated that minced meat treated with *M. fragrans* extracts exhibited a 1.8 log CFU/g reduction in *Staphylococcus aureus* and *Escherichia coli* populations within 48 h of storage. Similarly, Zhang et al. [72] found that in poultry samples, *M. fragrans* essential oil at 0.5 % concentration reduced bacterial counts by 2 log CFU/g, indicating strong enzyme inhibitory effects. By disrupting quorum sensing (QS) pathways, *M. fragrans* interferes with bacterial communication and biofilm formation. Oo et al. [73] reported a 60 % reduction in biofilm formation on food contact surfaces treated with *M. fragrans*, which enhanced food safety and extended shelf life. In a study on ready-to-eat vegetables, Cruz et al. [56] found that *M. fragrans* reduced QS-regulated virulence factors by 40 %, resulting in a 1.5 log CFU/g reduction in *Listeria monocytogenes*. Lipophilic compounds, such as myristicin, in *M. fragrans* destabilize bacterial cell membranes, leading to cell lysis. Sarıcaoglu and Turhan [64] observed that chicken meat treated with nutmeg essential oil showed a 2.5 log CFU/g reduction in total bacterial counts and an extended shelf life of up to 7 days when stored at 4 °C. Additionally, Bazaraa et al. [74] demonstrated a similar effect in seafood samples, where *M. fragrans* essential oil applied at 1 % concentration resulted in a 3 log CFU/g reduction in *V. parahaemolyticus* after 5 days of storage. *M. fragrans* compounds have been shown to function synergistically with other natural preservatives. Abd Algaffar et al. [75] reported that bread treated with nutmeg extracts and rosemary essential oil prevented mold growth and extended shelf life by 60 % compared with untreated samples. Combined treatment reduced fungal counts by over 3 log CFU/g, indicating enhanced efficacy when used in conjunction with other preservatives. These studies suggest that incorporating *M. fragrans* into food matrices can increase shelf life by 30–60 %, depending on its concentration and food type. Its multi-targeted antimicrobial mechanisms make *M. fragrans* a powerful natural alternative to synthetic preservatives, ideal for applications in dairy, meat, seafood, and bakery products.

6.3. Potential as a natural alternative to synthetic preservatives

The growing consumer desire for natural, clean-label preservatives

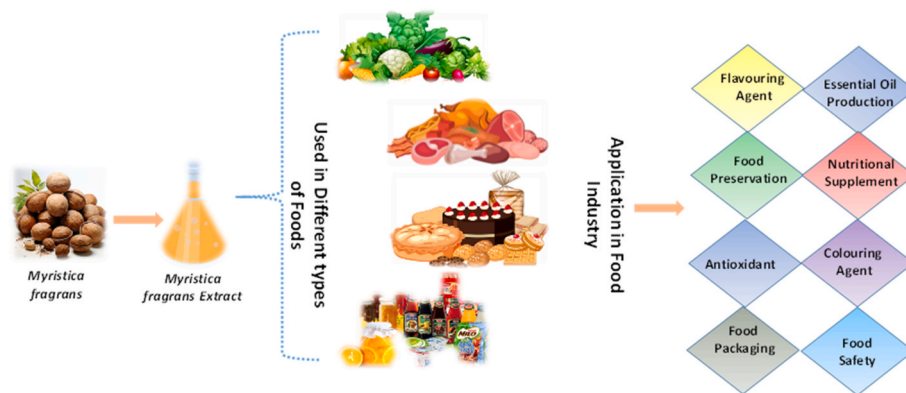


Fig. 5. Illustrating the application of *M. fragrans* (nutmeg) in the food industry.

has heightened the interest in *M. fragrans* as a feasible substitute for synthetic chemicals. Essential oils extracted from *M. fragrans* significantly prolong the shelf life of food items while preserving their quality and flavor. In contrast to synthetic preservatives, which may present health hazards, *M. fragrans* offers a safe and consumer-friendly alternative [14]. Notably, *M. fragrans* essential oils have been shown to retain antimicrobial efficacy when used in synergy with other natural preservatives, thereby enhancing overall food safety.

Quantitative studies highlight *M. fragrans* in extending shelf life and controlling spoilage. For example, Akanbi et al. [76] demonstrated that nutmeg extract, when incorporated into bread at a concentration of 0.4 %, effectively prevented mold growth and extended shelf life by 60 % compared with untreated samples. Similarly, nutmeg extract in bakery products reduced mold counts by 2 log CFU/g after five days of storage. These findings suggest that *M. fragrans* is a natural substitute for synthetic preservatives in baked goods.

In combination with other natural preservatives, *M. fragrans* exhibits synergistic effects that boost the preservation efficiency. Maurya et al. [77] reported that when *M. fragrans* essential oil was combined with rosemary extract in processed meat products, it extended shelf life by approximately 40 % and reduced bacterial counts by 1.5–2.0 log CFU/g compared to either treatment alone. This synergistic action not only reduces spoilage, but also enhances the antimicrobial spectrum, making *M. fragrans* a sustainable choice for clean-label products. By incorporating *M. fragrans* extracts or essential oils into food matrices, manufacturers can meet consumer preferences for natural ingredients and reduce the use of synthetic additives. The combined benefits of enhanced antimicrobial efficacy, extended shelf life, and alignment with clean-label trends make *M. fragrans* an attractive solution for natural food preservation. Fig. 5 illustrates the application of *M. fragrans* (nutmeg) in the food industry.

7. Conclusion and future prospects

This review revealed that *M. fragrans* (L.) has promising prospects for application as a natural antibacterial food ingredient against foodborne bacteria. Alkaloids, including myristicin, eugenol, and elimicin, have shown in vitro antibacterial properties because of their effects on cell membrane integrity and are the most important enzymes involved in bacterial growth and division. Based on the results of this study, it can be concluded that *M. fragrans* has the potential to increase food shelf life and decrease foodborne pathogens, leading towards an approach for future food safety and preservation. Exploiting these antibacterial properties presents a possibility for an effective natural and environmentally friendly food preservation system to minimize the number of foodborne diseases, and is applied mainly in developing countries where health care and clean water are scarce.

However, these encouraging outcomes indicate that there are some

challenges and research questions that need to be resolved to make better use of *M. fragrans*. Because the provision of a consistently bioactive product depends on the consistency and standardization of cultivation, the set and targets for harvesting, and extraction methods for bioactive compounds, this is a challenge. Although the specific mechanisms of action have been described, the molecular basis of these action plans is not fully clear. Biological applications demand scalability studies and the tests establishing the *in-vivo* safety tests to establish non-toxicity, allergenicity, or adverse lifetime consequences. More studies should be carried out to evaluate the efficiency of the extraction process, confirm the in vitro results in in vivo models, and examine the combined use of other natural antimicrobial agents. Overcoming these limitations will enable *M. fragrans* to deliver its full potential for food preservation, minimize food-borne diseases, and improve the health of the global population.

CRedit authorship contribution statement

Zaryab Shafi: Writing – original draft, Review and Editing. **Vinay Kumar Pandey:** Conceptualization, Project administration, Review and Editing. **Umme Habiba:** Review and Editing, Formal analysis. **Rahul Singh:** Supervision, Review and Editing, Project administration. **Mohammad Shahid:** Methodology, Review and Editing. **Sarvesh Rustagi:** Review and Editing, Formal analysis. **Béla Kovács:** Writing-Review and editing, Supervision, Funding acquisition. **Ayaz Mukarram Shaikh:** Writing- review and editing, Methodology, Investigation, Software.

Funding

Project No. TKP2021-NKTA-32 was implemented with support from the National Research, Development, and Innovation Fund of Hungary, financed by the TKP2021-NKTA funding scheme and supported by the University of Debrecen Program for Scientific Publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors express their deep gratitude to Integral University, Lucknow-226026, India, for their generous support of this work and for providing the manuscript communication number (IU/R&D/2024-MCN0003137). All authors are also thankful to the Faculty of Agriculture, Food Science, and Environmental Management, Institute of Food

Science, University of Debrecen, for their collaboration and support.

Data availability

No data was used for the research described in the article.

References

- [1] World Health Organization, J. Food Saf. (2020). <https://www.who.int/news-room/fact-sheets/detail/food-safety>.
- [2] Centers for Disease Control and Prevention, Foodborne germs and illnesses. <https://www.cdc.gov/foodsafety/foodborne-germs.html>, 2021.
- [3] G.E.S. El-Saber Batiha, D.E. Hussein, A.M. Algammal, T.T. George, P. Jeandet, A. E. Al-Snafi, A. Tiwari, J.P. Pagnossa, C.M. Lima, N.D. Thorat, M. Zahoor, M. El-Esawi, A. Dey, S. Alghamdi, H.F. Hetta, N. Cruz-Martins, Application of natural antimicrobials in food preservation: recent views, Food Control 126 (2021) 108066, <https://doi.org/10.1016/j.foodcont.2021.108066>.
- [4] M.A. Ibrahim, C.L. Cantrell, E.A. Jeliakova, T. Astatkie, V.D. Zheljzakov, Utilization of nutmeg (*Myristica fragrans* Houtt.) seed hydrodistillation time to produce essential oil fractions with varied compositions and pharmacological effects, Molecules 25 (2020) 565, <https://doi.org/10.3390/molecules25030565> [PubMed: 32012955].
- [5] A.M.E. Sulieyman, E.M. Abdallah, N.A. Alanazi, A. Ed-Dra, A. Jamal, H. Idriss, S. A. Shommo, Spices as sustainable food preservatives: a comprehensive review of their antimicrobial potential, Pharmaceuticals 16 (10) (2023) 1451.
- [6] T. Oo, B. Saiboonjan, S. Srijampa, A. Srisrattakarn, K. Sutthanut, R. Tavichakorntrakool, A. Chanawong, A. Lulitanond, P. Tippayawat, Inhibition of bacterial efflux pumps by crude extracts and essential oil from *Myristica fragrans* Houtt. (Nutmeg) seeds against methicillin-resistant *Staphylococcus aureus*, Molecules 26 (2021) 4662, <https://doi.org/10.3390/molecules26154662> [PubMed: 34361815].
- [7] K. Ashokkumar, J. Simal-Gandara, M. Murugan, M.K. Dhanya, A. Pandian, Nutmeg (*Myristica fragrans* Houtt.) essential oil: a review on its composition, biological, and pharmacological activities, Phytother. Res. 36 (2022) 2839–2851, <https://doi.org/10.1002/ptr.7491> [PubMed: 35567294].
- [8] A. Al-Mariri, R. Ismail, A. Allaham, B. Alobeid, L. Alhallab, Inhibitory effects of essential oils of Cinnamon zeylanicum and *Myristica fragrans* against *Brucella abortus* 544 inoculated in fresh Baladi cheese, J. Food Qual. Hazards Control (2021), <https://doi.org/10.18502/jfqc.8.1.5461>.
- [9] I. Matulyte, A. Jekabsone, L. Jankauskaite, P. Zavistanaviciute, V. Sakiene, E. Bartkiene, M. Ruzauskas, D.M. Kopustinskiene, A. Santini, J. Bernatoniene, The essential oil and hydrolats from *Myristica fragrans* seeds with magnesium aluminometasilicate as excipient: antioxidant, antibacterial, and anti-inflammatory activity, Foods 9 (2020) 37, <https://doi.org/10.3390/foods9010037> [PubMed: 31906495].
- [10] B. Xu, X. Wang, H. Wang, L. Cao, Y. Ge, B. Yuan, R. Gao, J. Li, Efficacy and safety of herbal formulas with the function of gut microbiota regulation for gastric and colorectal cancer: a systematic review and meta-analysis, Front. Cell. Infect. Microbiol. 12 (2022) 875225, <https://doi.org/10.3389/fcimb.2022.875225> [PubMed: 35992176].
- [11] J.V. Setty, I. Srinivasan, R.T. Sathiesh, M. Kale, V.V. Shetty, S. Venkatesh, In vitro evaluation of antimicrobial effect of *Myristica fragrans* on common endodontic pathogens, J. Indian Soc. Pedod. Prev. Dent. 38 (2020) 145–151, https://doi.org/10.4103/JISPPD.JISPPD_214_20 [PubMed: 32611860].
- [12] B. Khameneh, N.A.M. Eskin, M. Iranshahy, B.S. Fazly Bazzaz, Phytochemicals: a promising weapon in the arsenal against antibiotic-resistant bacteria, Antibiotics 10 (2021) 1044, <https://doi.org/10.3390/antibiotics10091044> [PubMed: 34572626].
- [13] Sarengaowa, L. Wang, Y. Liu, C. Yang, K. Feng, W. Hu, Effect of ascorbic acid combined with modified atmosphere packaging for browning of fresh-cut eggplant, Coatings 12 (10) (2022) 1580.
- [14] Z. Kiarsi, M. Hojjati, B.A. Behbahani, M. Noshad, In vitro antimicrobial effects of *Myristica fragrans* essential oil on foodborne pathogens and its influence on beef quality during refrigerated storage, J. Food Saf. 40 (2020) e12782, <https://doi.org/10.1111/jfs.12782>.
- [15] A. Ali, M. Yasir, M.I. Jilani, S. Shoaib, M. Latif, A. Ahmad, A. Nazir, Chemical composition and in vitro evaluation of cytotoxicity, antioxidant and antimicrobial activities of essential oil extracted from *Myristica fragrans* Houtt, Pol. J. Environ. Stud. 30 (2021).
- [16] Y.X. Li, F. Erhunmwunsee, M. Liu, K. Yang, W. Zheng, J. Tian, Antimicrobial mechanisms of spice essential oils and application in food industry, Food Chem. 382 (2022) 132312, <https://doi.org/10.1016/j.foodchem.2022.132312> [PubMed: 35158267].
- [17] D.A.N. Ansari Abdullah, Q.M. Siddique, A. Sayed, M. Ashfaque, Broad Spectrum Activities of Jaiphal (Nutmeg) in Una Ni System of Medicine: A Review, 2021.
- [18] N. Joseph, P. Reshma, Biochemical diversity in nutmeg. J agric technol, Agric. Technol. 56 (8) (2021) 56–61.
- [19] D. Rahardiyana, M. Poluakan, E.M. Moko, Physico-chemical properties of nutmeg (*Myristica fragrans* Houtt) of north Sulawesi nutmeg, Fullerene J. Chem. 5 (2020) 23–31, <https://doi.org/10.37033/fjc.v5i1.146>.
- [20] V. Kaur, S. Kaushal, D. Heena, D. Utreja, Occurrence, isolation, pharmacological potential, metabolism, and toxicity of myristicin: a naturally occurring alkoxy-substituted allylbenzene, Mini-Reviews Org. Chem. 21 (2024) 477–493, <https://doi.org/10.2174/1570193X2066230314105024>.
- [21] E.F. Seneme, D.C. Dos Santos, E.M.R. Silva, Y.E.M. Franco, G.B. Longato, Pharmacological and therapeutic potential of myristicin: a literature review, Molecules 26 (2021) 5914, <https://doi.org/10.3390/molecules26195914> [PubMed: 34641457].
- [22] J.Y. Jeong, I.G. Jung, S.H. Yum, Y.J. Hwang, In vitro synergistic inhibitory effects of plant extract combinations on bacterial growth of methicillin-resistant *Staphylococcus aureus*, Pharmaceuticals 16 (2023) 1491, <https://doi.org/10.3390/ph16101491> [PubMed: 37895962].
- [23] J.K. Dzotam, V. Kuetse, *Myristica fragrans* as a potential source of antibacterial agents, in: Advances in Botanical Research, Academic Press, Cambridge, USA, 2023, p. 107, <https://doi.org/10.1016/bs.abr.2022.08.017>.
- [24] V. Nikolic, L. Nikolic, A. Dinic, I. Gajic, M. Urosevic, L. Stanojevic, J. Stanojevic, B. Danilovic, Chemical composition, antioxidant and antimicrobial activity of nutmeg (*Myristica fragrans* Houtt.) seed essential oil, J. Essential Oil Bearing Plants 24 (2021) 218–227, <https://doi.org/10.1080/0972060X.2021.1907230>.
- [25] L.E. Marchese, S.A. McNaughton, G.A. Hendrie, K. Wingrove, K.M. Dickinson, K. M. Livingstone, A scoping review of approaches used to develop plant-based diet quality indices, Curr. dev. nutr. 7 (4) (2023) 100061.
- [26] L. Zhou, Y. Zhang, Y. Ge, X. Zhu, J. Pan, Regulatory mechanisms and promising applications of quorum sensing-inhibiting agents in control of bacterial biofilm formation, Front. Microbiol. 11 (2020) 589640, <https://doi.org/10.3389/fmicb.2020.589640> [PubMed: 33178172].
- [27] W. Zhou, Y. He, X. Lei, L. Liao, T. Fu, Y. Yuan, X. Huang, L. Zou, Y. Liu, R. Ruan, J. Li, Chemical composition and evaluation of antioxidant activities, antimicrobial, and anti-melanogenesis effect of the essential oils extracted from *Dalbergia pinnata* (Lour.) Prain, J. Ethnopharmacol. 254 (2020) 112731, <https://doi.org/10.1016/j.jep.2020.112731> [PubMed: 32135240].
- [28] T. Hou, S.S. Sana, H. Li, Y. Xing, A. Nanda, V.R. Netala, Z. Zhang, Essential oils and their antibacterial, antifungal and anti-oxidant activity applications: a review, Food Biosci. 47 (2022) 101716, <https://doi.org/10.1016/j.fbio.2022.101716>.
- [29] M. Meenu, B. Padhan, M. Patel, R. Patel, B. Xu, Antibacterial activity of essential oils from different parts of plants against *Salmonella* and *Listeria* spp, Food Chem. 404 (2023) 134723, <https://doi.org/10.1016/j.foodchem.2022.134723> [PubMed: 36444084].
- [30] S. Vuković, D. Moravčević, S. Jelčić, A. Vujošević, I. Pečinar, S. Kilibarda, A.Ž. Kostić, Phytochemical properties of nutmeg (*Myristica fragrans*), in: Agricultural, Biological & Life Science Conference, V. International, 2023, 260–260.
- [31] R.N. Cavalcanti, C.C. Koshima, T. Forster-Carneiro, M.T.M.S. Gomes, M. A. Rostagno, J.M. Prado, M.A.A. Meireles, Uses and Applications of Extracts from Natural Sources, 2022.
- [32] S. Jafarzadeh, S.M. Jafari, A. Salehabadi, A.M. Nafchi, U.S. Uthaya Kumar, H.P.S. A. Khalil, Biodegradable green packaging with antimicrobial functions based on the bioactive compounds from tropical plants and their by-products, Trends Food Sci. Technol. 100 (2020) 262–277, <https://doi.org/10.1016/j.tifs.2020.04.017>.
- [33] M. Muzolf-Panek, K. Stuper-Szablewska, Comprehensive study on the antioxidant capacity and phenolic profiles of black seed and other spices and herbs: effect of solvent and time of extraction, J. Food Meas. Char. 15 (2021) 4561–4574, <https://doi.org/10.1007/s11694-021-01028-z>.
- [34] M. El-Hefny, M.Z.M. Salem, S.I. Behiry, H.M. Ali, The potential antibacterial and antifungal activities of wood treated with *Withania somnifera* fruit extract, and the phenolic, caffeine, and flavonoid composition of the extract according to HPLC, Processes 8 (2020) 113, <https://doi.org/10.3390/pr8010113>.
- [35] C.A. Juan, J.M. Pérez de la Lastra, F.J. Plou, E. Pérez-Lebeña, The chemistry of reactive oxygen species (ROS) revisited: outlining their role in biological macromolecules (DNA, lipids and proteins) and induced pathologies, Int. J. Mol. Sci. 22 (2021) 4642, <https://doi.org/10.3390/ijms22094642> [PubMed: 33924958].
- [36] F. Nourbakhsh, M. Lotfalizadeh, M. Badpeyma, A. Shakeri, V. Soheili, From plants to antimicrobials: natural products against bacterial membranes, Phytother. Res. 36 (2022) 33–52, <https://doi.org/10.1002/ptr.7275> [PubMed: 34532918].
- [37] F.J. Álvarez-Martínez, E. Barrajón-Catalán, M. Herranz-López, V. Micol, Antibacterial plant compounds, extracts and essential oils: an updated review on their effects and putative mechanisms of action, Phytomedicine 90 (2021) 153626, <https://doi.org/10.1016/j.phymed.2021.153626> [PubMed: 34301463].
- [38] E. Teshome, S.F. Forsido, H.P.V. Rupasinghe, E. Olika Keyata, Potentials of natural preservatives to enhance food safety and shelf life: a review, TheScientificWorldJOURNAL 2022 (2022) 9901018, <https://doi.org/10.1155/2022/9901018> [PubMed: 36193042].
- [39] A. Biharee, A. Sharma, A. Kumar, V. Jaitak, Antimicrobial flavonoids as a potential substitute for overcoming antimicrobial resistance, Fitoterapia 146 (2020) 104720, <https://doi.org/10.1016/j.fitote.2020.104720> [PubMed: 32910994].
- [40] B.E. Omoruyi, G. Bradley, A.J. Afolayan, Antioxidant and phytochemical properties of *Carpobrotus edulis* (L.) bolus leaf used for the management of common infections in HIV/AIDS patients in Eastern Cape Province, BMC complement. altern. med. 12 (2012) 1–9.
- [41] D. Zhang, R.Y. Gan, A.K. Farha, G. Kim, Q.Q. Yang, X.M. Shi, C.L. Shi, Q.X. Luo, X. B. Xu, H.B. Li, H. Corke, Discovery of antibacterial dietary spices that target antibiotic-resistant bacteria, Microorganisms 7 (2019) 157, <https://doi.org/10.3390/microorganisms7060157> [PubMed: 31146495].
- [42] A. Malik, M. Li, M. Lenzen, J. Fry, N. Liyanapathirana, K. Beyer, M. Prokopenko, Impacts of climate change and extreme weather on food supply chains cascade across sectors and regions in Australia, Nat. Food 3 (8) (2022) 631–643.
- [43] S.M. Hadi, A.M. Etheb, A.H. Omran, S.H. Hassan, Characterization, biofilm and plasmid curing effect of silver nanoparticles synthesis by aqueous extract of *Myristica fragrans* seeds, Biological 15 (2022) 1149.

- [44] M.I. Shafiq, M. Ahmed, A. Rasul, Z.Q. Samra, M.A. Qadir, S. Mazhar, A. Ali, Chemical composition of the essential oils of nutmeg and mace by GC-FID/MS indigenous to Pakistan and evaluation of their biological activities, *Lat. Am. J. Pharm.* 35 (10) (2016) 2176–2184.
- [45] S.S. Al-Rawi, A.H. Ibrahim, H.J. Ahmed, Z.O. Khudhur, Therapeutic, and pharmacological prospects of nutmeg seed: a comprehensive review for novel drug potential insights, *Saudi Pharmaceut. J.* 102067 (2024).
- [46] M.T. Ha, N.K. Vu, T.H. Tran, J.A. Kim, M.H. Woo, B.S. Min, Phytochemical and pharmacological properties of *Myristica fragrans* Houtt.: an updated review, *Arch Pharm. Res. (Seoul)* 43 (2020) 1067–1092, <https://doi.org/10.1007/s12272-020-01285-4> [PubMed: 33206347].
- [47] J. Schuh, P. Batisteli, A. Gargetti, A. Zapparoli, T.I. Balsan, A. Gilioli, V.C. Zanetti, F.B. Foralosso, Á. Vargas Junior, N. Fronza, S. Verruck, S.M.D. Silveira, Basil, marjoram, nutmeg and oregano essential oils as natural preservatives of Quark-type cheese, *Food Sci. Technol.* 42 (2022) e31322, <https://doi.org/10.1590/fst.31322>.
- [48] P.A. Okiki, C.P. Nwobi, O.B. Akpor, E. Adewole, R.D. Agbana, Assessment of nutritional and medicinal properties of nutmeg, *Scientific African* 19 (2023) e01548.
- [49] C. Singh, R. Kumar, J.N. Umeshbhai, Role of spices and herbs in human health: a review, *Indian J. Health ; Wellbeing* 11 (2020).
- [50] A. Garnier, F. Shahidi, Spices and herbs as immune enhancers and anti-inflammatory agents: a review, *J. Food Bioact.* 14 (2021).
- [51] M.T. Sultan, F. Saeed, H. Raza, A. Ilyas, F. Sadiq, A. Musarrat, M. Afzaal, M. Hussain, M.A. Raza, E. Al Jbawi, Nutritional and therapeutic potential of nutmeg (*Myristica fragrans*): a concurrent review, *Cogent Food Agric.* 9 (2023) 2279701, <https://doi.org/10.1080/23311932.2023.2279701>.
- [52] R. Suwarda, R.F. Suneth, D. Sondari, Potential and opportunities of nutmeg pericarp as functional foods, in: *E3S Web of Conferences*, vol. 306, EDP Sciences, 2021 04007.
- [53] G. Singh, A.K. Passari, V.V. Leo, V.K. Mishra, S. Subbarayan, P. Singh, B. Kumar, Nutmeg extracts efficacy in enhancing the shelf life of milk: a comparative study, *Adv. Dairy Res.* 8 (2020) 1–5.
- [54] J.K. Dzutain, V. Kuet, *Myristica fragrans* as a potential source of antibacterial agents, in: *Advances in Botanical Research* Vol. 107, Academic Press, 2023, pp. 213–237.
- [55] Y. Kang, J. Liu, Y. Jiang, S. Yin, Z. Huang, Y. Zhang, J. Wu, L. Chen, L. Shao, Understanding the interactions between inorganic-based nanomaterials and biological membranes, *Adv. Drug Deliv. Rev.* 175 (2021) 113820, <https://doi.org/10.1016/j.addr.2021.05.030> [PubMed: 34087327].
- [56] A. Cruz, E. Sánchez-Hernández, A. Teixeira, R. Oliveira, A. Cunha, P. Martín-Ramos, Phytoconstituents and ergosterol biosynthesis-targeting antimicrobial activity of nutmeg (*Myristica fragrans* houtt.) against Phytopathogens, *Molecules* 29 (2024) 471, <https://doi.org/10.3390/molecules29020471> [PubMed: 38257384].
- [57] M. Liang, X. Ge, H. Xua, K. Ma, W. Zhang, Y. Zan, T. Efferth, Z. Xue, X. Hua, Phytochemicals with activity against methicillin-resistant *Staphylococcus aureus*, *Phytomedicine* 100 (2022) 154073, <https://doi.org/10.1016/j.phymed.2022.154073> [PubMed: 35397285].
- [58] S.I.U. Mevo, M. Ashrafudoulla, M. Furkanur Rahaman Mizan, S.H. Park, S.D. Ha, Promising strategies to control persistent enemies: some new technologies to combat biofilm in the food industry—a review, *Compr. Rev. Food Sci. Food Saf.* 20 (2021) 5938–5964, <https://doi.org/10.1111/1541-4337.12852> [PubMed: 34626152].
- [59] S. Balakrishnan, K.S. Ibrahim, S. Duraisamy, I. Sivaji, S. Kandasamy, A. Kumarasamy, N.S. Kumar, Antiquorum sensing and antibiofilm potential of biosynthesized silver nanoparticles of *Myristica fragrans* seed extract against MDR *Salmonella enterica* serovar Typhi isolates from asymptomatic typhoid carriers and typhoid patients, *Environ. Sci. Pollut. Res. Int.* 27 (2020) 2844–2856, <https://doi.org/10.1007/s11356-019-07169-5> [PubMed: 31836973].
- [60] D. Zhang, R.Y. Gan, J.R. Zhang, A.K. Farha, H.B. Li, F. Zhu, X.H. Wang, H. Corke, Antivirulence properties and related mechanisms of spice essential oils: a comprehensive review, *Compr. Rev. Food Sci. Food Saf.* 19 (2020) 1018–1055, <https://doi.org/10.1111/1541-4337.12549> [PubMed: 33331691].
- [61] M. Kaur, A.K. Singh, A. Singh, Bioconversion of food industry waste to value added products: Current technological trends and prospects, *Food Biosci.* 102935 (2023).
- [62] G. Arumugam, B. Purushotham, M.K. Swamy, *Myristica fragrans* Houtt.: botanical, pharmacological, and toxicological aspects, in: *Natural Bio-active Compounds: Volume 2: Chemistry, Pharmacology and Health Care Practices*, 2019, 81–106.
- [63] A.K.P. Jauhari, J.G.S. Riseno, H. Hidrotunnisa, Microencapsulation of nutmeg essential oil (*Myristica fragrans*) via spray drying: effects of feed emulsion parameters on emulsion and powder characteristics, *Adv. Food Sci., Sustain. Agric. Agroindust. Eng. (AFSSAAE)* 5 (2022).
- [64] F.T. Sarıcaoglu, S. Turhan, Physicochemical, antioxidant and antimicrobial properties of mechanically deboned chicken meat protein films enriched with various essential oils, *Food Packag. Shelf Life* 25 (2020) 100527, <https://doi.org/10.1016/j.foodpack.2020.100527>.
- [65] C. Xedzro, K. Tano-Debrah, H. Nakano, Antibacterial efficacies and time-kill kinetics of indigenous Ghanaian spice extracts against *Listeria monocytogenes* and some other food-borne pathogenic bacteria, *Microbiol. Res.* 258 (2022) 126980, <https://doi.org/10.1016/j.micres.2022.126980> [PubMed: 35158300].
- [66] A. da Silva Ramos, P.H.C. Félix, B.E. Teixeira-Costa, Use of essential oils in food industries—application as functional compounds in food matrices and packaging, in: *Essential Oils*, CRC Press, 2024, pp. 61–78.
- [67] O.O. Osemwegie, A.A. Adeyanju, D.E. Rotimi, F.Y. Daramola, C.O. Adetunji, F. B. Lewu, A.T. Odeyemi, Biopreservative effects of essential oils in the food industry: oils and nuts, seeds and, seed products, in: *Applications of Essential Oils in the Food Industry*, Academic Press, 2024, pp. 305–323.
- [68] T.B. Leta, J.O. Adeyemi, O.A. Fawole, Utilizing fruit waste-mediated nanoparticles for sustainable food packaging materials to combat food loss and waste, *Food Biosci.* 104151 (2024).
- [69] Z. Shafi, V.K. Pandey, R. Singh, S. Rustagi, Carbon dots-nanosensors: advancement in food traceability for a sustainable environmental development, *Food Control* 110693 (2024).
- [70] V.K. Pandey, Z. Shafi, A. Tripathi, G. Singh, R. Singh, S. Rustagi, Production of biodegradable food packaging from mango peel via enzymatic hydrolysis and polyhydroxyalkanoates synthesis: a review on microbial intervention, *Curr. Res. Microb. Sci.* (2024) 100292.
- [71] A. Cruz, E. Sánchez-Hernández, A. Teixeira, R. Oliveira, A. Cunha, P. Martín-Ramos, Phytoconstituents and ergosterol biosynthesis-targeting antimicrobial activity of nutmeg (*Myristica fragrans* houtt.) against Phytopathogens, *Molecules* 29 (2) (2024) 471.
- [72] Z. Zhang, X. Liu, Z. Shen, Y. Chen, C. Chen, Y. SiTu, T. Jiang, Isoflavaspidic acid PB extracted from *Dryopteris fragrans* (L.) Schott inhibits *Trichophyton rubrum* growth via membrane permeability alteration and ergosterol biosynthesis disruption, *BioMed Res. Int.* 2022 (1) (2022) 6230193.
- [73] T. Oo, B. Saiboonjan, U. Mongmonsin, S. Srijanpa, A. Srirattakarn, R. Tavichakorntrakool, P. Tippayawat, Effectiveness of co-cultured *Myristica fragrans* Houtt. seed extracts with commensal *Staphylococcus epidermidis* and its metabolites in antimicrobial activity and biofilm formation of skin pathogenic bacteria, *BMC Complement. Med. Ther.* 24 (2024) 380.
- [74] W.A. Bazarara, A.E.N.A. Khattab, E.M. Osman, M.R. Ali, Extension of chicken fillets shelf life using genetically improved probiotic strain and chitosan, *Food Control* 168 (2025) 110827.
- [75] S.O. Abd Algaffar, P. Satyal, N.S. Ashmawy, A. Verbon, W.W. van de Sande, S. A. Khalid, In vitro and in vivo wide-spectrum dual antimycetomal activity of eight essential oils coupled with chemical composition and metabolomic profiling, *Microbiol. Res.* 15 (3) (2024) 1280–1297.
- [76] O.D. Akanbi, A.A. Folorunso, Organoleptic profiles of bread produced using various natural flavours, *Afr. J. Food Nutr. Sci.* 22 (2022) 20053–20066, <https://doi.org/10.18697/ajfand.109.19910>.
- [77] A. Maurya, J. Prasad, S. Das, A.K. Dwivedy, Essential oils and their application in food safety, *Front. Sustain. Food Syst.* 5 (2021) 653420, <https://doi.org/10.3389/fsufs.2021.653420>.