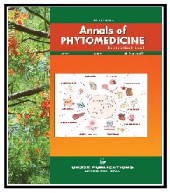
Annals of Phytomedicine 13(2): 230-237, 2024

DOI: http://dx.doi.org/10.54085/ap.2024.13.2.22

Annals of Phytomedicine: An International Journal
http://www.ukaazpublications.com/publications/index.php

Print ISSN : 2278-9839 Online ISSN : 2393-9885



Review Article : Open Access

Exploring the therapeutic potential of bioactive compounds in spices and herbs: Preclinical evidence and medicinal applications

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Article Info

Article history
Received 6 August 2024
Revised 19 September 2024
Accepted 20 September 2024
Published Online 30 December 2024

Keywords
Metabolomic compounds
Therapeutic potential
Herbal tablets
Drug industry

Abstract

This article explores the therapeutic potential of bioactive compounds found in spices and herbs, focusing on preclinical evidence and their medicinal applications. Spices and herbs have been utilized for centuries in traditional medicine due to their diverse range of bioactive compounds, which exhibit a variety of health-promoting properties. The review synthesizes current research on the pharmacological effects of these compounds, including their anti-inflammatory, antioxidant, antimicrobial and anticancer activities. By examining preclinical studies, the article highlights how these bioactive compounds can modulate biological pathways and offer potential therapeutic benefits. The discussion also covers the mechanisms through which these compounds exert their effects and the implications for developing novel treatments. The evidence underscores the importance of integrating spices and herbs into modern therapeutic practices and encourages further research to fully understand their medicinal value.

1. Introduction

Herbal medicine, deeply rooted in ancient traditions, has long been a cornerstone of healthcare, providing natural remedies for various ailments across civilizations. Despite the dominance of modern pharmaceuticals, the global reliance on herbal medicine has seen a resurgence, particularly in countries like India, where over 70% of the population depends on non-allopathic systems such as Ayurveda, Unani and Siddha (Bhowmik *et al.*, 2009). This renewed interest in herbal treatments is driven by their natural origins, perceived safety, cost-effectiveness and fewer side effects compared to synthetic drugs. However, the increased use of herbal products has also brought to light significant concerns regarding their safety, efficacy and quality. While historically considered safe due to their traditional use, instances of contamination and adulteration have raised alarms about potential side effects. The holistic nature of herbal medicine presents challenges in assessing its efficacy, but integrating modern scientific methodologies offers a path toward better standardization and quality control (Chaudhari *et al.*, 2021).

India, with its vast biodiversity and deep reservoir of traditional knowledge, holds a crucial position in the global medicinal plant market. The country's rich array of bioactive compounds, particularly antioxidants, not only contributes to therapeutic applications but also supports the development of functional foods (Chaudhari *et al.*, 2021). To fully harness this potential, there is an urgent need to ensure that herbal products meet rigorous standards of quality and safety. Poorly standardized products risk diminishing the credibility of herbal medicine, which is why pharmacists play a pivotal role in this evolving field. By staying informed about the latest developments in herbal medicine and its interactions with conventional treatments, pharmacists can guide patients effectively and advocate for the use of high-quality, GMP-compliant products (Craker and Simon, 1992). Moreover, the integration of modern scientific techniques with traditional herbal knowledge is essential for developing herbal medicines that are not only effective and safe but also scientifically validated. This approach will help enhance the global reputation of herbal medicine, ensuring its continued relevance and reliability as a key component of healthcare. Additionally, the documentation and preservation of traditional knowledge, especially within indigenous communities, is critical (Peter and Babu, 2012). Bioactive compounds (BACs) from natural sources, such as seeds, fruits and fermented products, have garnered significant attention for their potential health benefits. These compounds, including flavonoids, phenolic acids and carotenoids, are critical in developing functional foods that may provide therapeutic effects beyond basic nutrition (Banwo *et al.*, 2021). BACs are recognized for their diverse health-promoting properties, such as antioxidant, anti-inflammatory, antidiabetic, anticancer and antiviral activities (Pascale *et al.*, 2022). They work by neutralizing free radicals and reactive oxygen species (ROS), which

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can cause cellular damage and contribute to various diseases. However, the bioavailability and effectiveness of BACs can be affected by factors such as the food matrix, molecular size and gastrointestinal conditions (Chaudhari *et al.*, 2021).

Functional foods, which offer health benefits beyond their nutritional value, often rely on BACs to provide these additional advantages. Despite the documented benefits, challenges such as bioavailability and the need for scientific validation persist. Techniques like encapsulation, including spray drying and freeze-drying, are employed to enhance the stability and delivery of BACs, yet further research is necessary to confirm their health claims and optimize their integration into functional foods (González-Aguilar *et al.*, 2008). Pharmacists play a crucial role in ensuring that herbal products and functional foods meet safety and quality standards. They must be aware of potential interactions between herbal remedies and conventional drugs and support the use of high-quality products (Mustafa *et al.*, 2017). Integrating modern scientific methods with traditional knowledge can advance the development of effective and safe herbal medicines (Kumar *et al.*, 2019). Future research should focus on evidence-based studies to validate the health benefits of BACs and address the challenges in their application. By overcoming these hurdles, the potential of BACs can be fully realized, paving the way for advancements in functional foods.

2. Classification of bioactive compounds in spices and herbs

Bioactive chemicals, essential components of functional foods, play a crucial role in health enhancement through their anti-inflammatory, antifungal and antioxidant properties in Table 1. These chemicals target biological systems to control, prevent and treat diseases, despite their small amounts in food. Overindulgence can be harmful, so clinical studies are necessary to establish safe limits. The Functional Food Center revised its definition in 2017, emphasizing that functional foods contain biologically active compounds that provide documented health benefits by targeting specific biomarkers, particularly in managing chronic diseases without the side effects of conventional medications. Examples include seaweeds, rich in bioactive compounds, which can prevent heart disease and herbal remedies used in cancer management. Clinical evidence supports the effectiveness of these bioactive compounds in functional foods, underscoring their role in improving quality of life and affirming their functional role in health and disease treatment (Martirosyan and Miller, 2018). The classification of bioactive compounds in spices and herbs (Palai *et al*., 2020; Rani *et al.,* 2023).

Table 1: Classification of bioactive compounds in spices and herbs

Bioactive group	Representative compounds	Biological role
Alkaloids	Capsaicin, Piperine, Caffeine, Theobromine	Capsaicin from chili peppers aids digestion and provides pain relief. Piperine from black pepper increases nutrient absorption. Caffeine acts as a central nervous system stimulant, improving alertness. Theobromine, present in chocolate, offers mild stimulation and supports heart health.
Flavonoids	Rutin, Luteolin, Kaempferol, Naringenin	Rutin helps strengthen blood vessels and reduce inflammation. Luteolin acts as an antioxidant with potential anticancer effects. Kaempferol supports heart health and lowers the risk of chronic diseases. Naringenin, found in citrus fruits, aids in DNA repair and inflammation reduction.
Minerals	Iron, Calcium, Magnesium, Potassium	Iron is essential for the formation of hemoglobin, enabling oxygen transport in the blood. Calcium is necessary for strong bones and teeth. Magnesium supports muscle and nerve function. Potassium helps maintain fluid balance and normal blood pressure.
Phenolic acids	Caffeic acid, Ferulic acid, Rosmarinic acid	Caffeic acid is an antioxidant that reduces inflammation. Ferulic acid protects against UV damage and supports skin health. Rosmarinic acid, found in herbs like rosemary, has antiallergic and anti-inflammatory properties.
Polyphenols	Curcumin, Quercetin, Resveratrol, Epicatechin	Curcumin exhibits anti-inflammatory and antioxidant effects. Quercetin promotes heart health and reduces inflammation. Resveratrol is linked to potential anti-aging benefits and cardiovascular protection. Epicatechin, found in green tea and cocoa, enhances vascular health.
Saponins	Diosgenin, Soyasapogenol	Diosgenin shows potential in reducing inflammation and cholesterol levels. Soyasapogenol, present in soy, may have cancer-preventive properties and enhances immune function.
Tannins	Catechins, Ellagitannins	Catechins, abundant in tea, are potent antioxidants that support cardiovascular health. Ellagitannins possess anticancer properties and contribute to digestive health by protecting the gut lining.
Terpenoids	Limonene, Menthol, Thymol, Carvacrol	Limonene has anti-inflammatory and antioxidant benefits. Menthol provides a cooling sensation and acts as a decongestant. Thymol and carvacrol, found in thyme and oregano, exhibit strong antimicrobial properties, useful in food preservation and natural antiseptic applications.
Vitamins	A, E, C, B6, B12, Folate	Vitamin A is crucial for healthy vision, immune system support and skin maintenance. Vitamin E functions as an antioxidant, protecting cells from oxidative stress. Vitamin C enhances immune defense and aids in collagen synthesis. B vitamins play a role in energy metabolism and red blood cell production.

2.1 Flavonoids in spices and herbs

Flavonoids are a diverse group of phytonutrients (plant chemicals) found in many fruits, vegetables, grains, bark, roots, stems, flowers, tea and wine. They are known for their powerful antioxidant properties and play a significant role in human health by neutralizing free radicals, reducing inflammation and lowering the risk of various chronic diseases. Among the wide variety of plant-based foods, spices and herbs are particularly rich sources of flavonoids, contributing not only to flavor and color but also to the health benefits of the diet (Awuchi, 2020).

2.2 Types of flavonoids in spices and herbs

Flavonoids are compounds found in spices and herbs, including flavonols, flavones, flavanones, flavanols, isoflavones and anthocyanins. Quercetin, found in onions, garlic and coriander, has anti-inflammatory and antioxidant properties, helping reduce blood pressure and prevent heart disease. Kaempferol, found in coriander, chives and dill, has anticancer properties, reducing chronic disease risk. Catechin, found in spices like cloves and fenugreek, has strong antioxidant properties and is associated with heart health, weight management and brain function improvement. Myricetin, found in herbs like thyme and oregano, has anti-inflammatory, anticancer and antidiabetic properties (Gupta, 2013). Flavonoid-rich spices and herbs include cinnamon, turmeric, coriander, garlic and thyme. Cinnamon is rich in quercetin and catechin, known for its anti-inflammatory and antioxidant properties. Turmeric contains curcumin, quercetin and kaempferol, providing additional antioxidant benefits. Coriander supports digestion, detoxification and heart health. Garlic is high in quercetin, known for its cardiovascular benefits, including cholesterol and blood pressure reduction. Thyme, rich in myricetin, has strong antioxidant and antimicrobial properties, supporting immune health and protecting against infections (Kaefer and Milner, 2008).

2.3 Phenolic acids

Phenolic compounds, found in spices, are essential for plant defense mechanisms and human health. They are derived through the shikimic acid and phenylpropanoid pathways, which are absent in animals and humans. Spices, known for their natural products, are a major source of these compounds, which have therapeutic significance due to their antioxidant, antimicrobial and anti-inflammatory properties. These compounds include hydroxybenzoic acids, hydroxycinnamic acids, flavonoids and complex phenolics. Hydroxybenzoic acids, including gallic acid, have strong antioxidant and anti-inflammatory properties. Hydroxycinnamic acids, including ferulic acid and caffeic acid, possess antioxidant, anti-inflammatory and antimicrobial activities. Ferulic acid reduces oxidative stress, while caffeic acid shows antibacterial and antifungal properties. Flavonoids and complex phenolics, such as quercetin and rutin, exhibit antioxidant, anti-inflammatory and cardiovascular protective effects (Yashin *et al.*, 2017).

Phenolic compounds are powerful antioxidants that neutralize free radicals, protecting cells from oxidative stress, which is linked to chronic diseases like cancer and cardiovascular diseases. They also have antimicrobial properties, such as cinnamic acid and its derivatives, which provide natural protection against microbial infections. Phenolics like gallic acid and curcumin also exhibit strong anti-inflammatory effects, inhibiting the activity of pro-inflammatory enzymes and cytokines, which are beneficial in managing inflammatory conditions like arthritis and inflammatory bowel disease (Sun and Shahrajabian, 2023).

2.4 Alkaloids

Alkaloids are a group of naturally occurring compounds found in plants, primarily nitrogenous, with significant pharmacological effects. They have been utilized in traditional medicine systems worldwide, particularly in spices like black pepper and fenugreek. Piperine, found in black pepper and long pepper, is known for its anti-inflammatory, antioxidant and antimicrobial properties. It has been used in Ayurvedic and Chinese medicine to treat digestive issues and enhance the bioavailability of other compounds. Trigonelline, predominantly found in fenugreek, is associated with hypoglycemic effects and neuroprotective properties. It has been used in Ayurvedic medicine and other traditional systems for its therapeutic effects on diabetes, digestive issues and inflammation (Rivera-Pérez *et al.*, 2023).

Fenugreek also contains 4-hydroxy-isoleucine, which is noted for its role in enhancing insulin sensitivity and potentially aiding in blood sugar regulation. Similar to trigonelline, fenugreek containing 4-hydroxy-isoleucine is used in traditional medicine for its supposed benefits in treating diabetes and metabolic disorders. The Piper genus contains various alkaloids, such as *Piper longum* (Pippali) and *Piper nigrum* (Black pepper). These plants have been used in Traditional Chinese Medicine (TCM), Ayurvedic Medicine and Folkloric Medicine (Zaveri *et al.*, 2010).

2.5 Terpenoids

Terpenoids are secondary metabolites derived from terpenes by adding functional groups, making them more diverse and often more complex than terpenes. They may include additional polar groups, making them more varied in their volatility. Examples of terpenes and terpenoids include limonene, pinene and menthol. Both terpenes and terpenoids play critical roles in plant defense by repelling herbivores, attracting predators and inhibiting the growth of competing plants or pathogens. Examples of terpenes and terpenoids used in food and fragrance industries include menthol for its cooling sensation and minty flavor in candies and personal care products and linalool for its floral scent in perfumes and cosmetics (Ludwiczuk *et al.*, 2017).

Medicinal applications of terpenes and terpenoids include anti-inflammatory, analgesic and anticancer effects. Examples include Cannabidiol (CBD) found in cannabis and Taxol (Paclitaxel) used in cancer treatment (Opitz *et al.*, 2020). Extraction methods for non-polar terpenes include hydrophobic solvents like hexane or dichloromethane, steam distillation for essential oils rich in terpenes and terpenoids and cold pressing for citrus oils. Analytical techniques include gas chromatography-mass spectrometry (GC-MS) for volatile and non-polar terpenes and high-performance liquid chromatography (HPLC) for terpenoids with higher polarity or less volatile compounds. Understanding these compounds' structure, function and extraction methods can enhance their application in various industries, from food and fragrance to medicine**.**

2.6 Saponins

Saponins are found in various spices and herbs, contributing to their health benefits and potential adverse effects. Some common spices and herbs contain saponins, such as ginseng (*Panax ginseng*), which

have adaptogenic properties, anti-inflammatory, antioxidant and immunostimulant effects. However, high doses may cause gastrointestinal issues or interact with medications (Patel and Rauf, 2017).

Licorice (*Glycyrrhiza glabra*) has antiviral, anti-inflammatory and immune-boosting properties but can lead to hypertension, hypokalemia and fluid retention (Leite *et al.*, 2022). Soapwort (*Saponaria officinalis*) is a major component of saponins and is traditionally used for cleansing properties and treating coughs and colds. High saponin content can cause gastrointestinal upset (Chandra *et al.*, 2021). Quinoa (*Chenopodium quinoa*) contains saponins naturally occurring in the seed coat, providing antioxidant and anti-inflammatory effects. However, unprocessed quinoa can be bitter and cause stomach irritation (Jacobsen, 2003). Fenugreek (*Trigonella foenum-graecum*) contains diosgenin, which has potential benefits in blood sugar regulation and cholesterol management but can cause gastrointestinal issues and allergic reactions (Idris *et al.*, 2021). Coriander (*Coriandrum sativum*) is known for its antioxidant and digestive benefits but can cause allergic reactions in sensitive individuals (Sharma and Chakraborty, 2019). Dandelion (*Taraxacum officinale*) contains various saponins and is used as a diuretic and for liver health. However, it can also cause allergic reactions and gastrointestinal upset in some individuals (Jalili *et al.*, 2020).

2.7 Essential oils in spices and herbs

Essential oils are aromatic compounds extracted from plants, such as spices and herbs, known for their strong fragrance and flavor. They are valuable in culinary, medicinal and industrial applications due to their distinctive aromas and flavors. Common essential oils include cinnamon, clove, pepper, cardamom, basil, oregano, thyme and rosemary. They can be extracted using various methods, such as steam distillation, hydrodistillation, solvent extraction, cold pressing and supercritical CO_2 extraction. Steam distillation evaporates the essential oil, hydrodistillation boils the plant material, solvent extraction preserves the integrity of the herbs, cold pressing releases the essential oils and supercritical CO_2 extraction uses carbon dioxide under high pressure. Essential oils have various applications, including culinary flavoring, medicinal use, cosmetic and fragrance industry and industrial use for cleaning products and air fresheners (Škrinjar and Nemet, 2009).

3. Mechanisms of action of bioactive compounds

3.1 Anti-inflammatory properties

Inflammation is a natural immune response to injury or infection, but chronic inflammation is linked to health issues like heart disease, arthritis and cancer. Spices and herbs possess anti-inflammatory properties, which can help reduce inflammation and contribute to overall health. Turmeric, with its active compound curcumin, inhibits several inflammatory pathways and cytokines, such as TNF-α and IL-6, making it a potent anti-inflammatory agent. Ginger, with its gingerol, inhibits the production of inflammatory cytokines and enzymes, helping manage conditions like osteoarthritis and muscle pain. Cinnamon, with its polyphenols and cinnamaldehyde, reduces inflammation markers, improving metabolic health and reducing the risk of chronic diseases. Cloves contain eugenol, which inhibits inflammatory enzymes and cytokines, making clove effective in reducing inflammation and associated pain. Black pepper's active component, piperine, has anti-inflammatory effects, modulating signaling pathways involved in inflammatory cytokine production (Mueller *et al.*, 2010).

Basil, Rosemary, Thyme, Sage and Mint are all anti-inflammatory herbs. Basil contains essential oils and polyphenols that inhibit inflammatory mediators and cytokines, while Rosemary is rich in rosmarinic acid and carnosic acid, which inhibit inflammatory enzymes and cytokines. Thyme's essential oils, particularly thymol and carvacrol, suppress inflammatory gene and protein expression, while Sage's compounds like rosmarinic acid and ursolic acid support overall health. Mint, with its menthol and other essential oils, provides symptomatic relief in conditions like respiratory inflammation and digestive issues. These herbs work together to reduce inflammation and promote overall health (Jungbauer and Medjakovic, 2012).

Anti-inflammatory properties of spices and herbs include inhibiting inflammatory enzymes like COX-2 and LOX, reducing the production of pro-inflammatory cytokines like TNF-α and IL-6, reducing oxidative stress and blocking inflammation pathways like the NF-κB pathway. These properties can reduce the risk of chronic diseases like cardiovascular disease, diabetes and cancer, improve joint health, enhance digestive health and provide pain relief from inflammation-related pain (Mueller *et al.*, 2010).

3.2 Antioxidant activity

Antioxidants are compounds that inhibit oxidation, a chemical reaction that produces free radicals leading to cellular damage. Spices and herbs are known for their antioxidant properties, which contribute to their health benefits (Wojdy³o *et al.*, 2007). Turmeric, a spice rich in curcumin, has been extensively studied for its anti-inflammatory and antioxidant properties. Cinnamon, rich in polyphenols and flavonoids, has strong antioxidant activity, helping combat oxidative stress and potentially lowering the risk of chronic diseases. Cloves, rich in eugenol, are effective in scavenging free radicals and protecting cells from oxidative damage. Black pepper, rich in piperine, has antioxidant properties, enhancing the bioavailability of other antioxidants and nutrients in the body. Ginger, known for its antioxidant compounds, including gingerol, has been shown to reduce oxidative stress and inflammation, contributing to its anti-inflammatory and health-promoting effects. Basil, Rosemary, Thyme, Mint and Sage are all rich in antioxidant-rich herbs. Basil is rich in polyphenols, flavonoids and essential oils that neutralize free radicals and protect cells from oxidative damage. Rosemary contains rosmarinic acid and other polyphenols, which help protect cells from oxidative stress and contribute to better cognitive and cardiovascular health. Thyme is rich in thymol and carvacrol, which have potent antioxidant properties. Mint contains flavonoids and phenolic acids, which neutralize free radicals and support digestive health. Sage is known for its high levels of rosmarinic acid, carnosic acid and other antioxidants, which contribute to its potential health benefits (Hinneburg *et al.*, 2006; Yashin *et al.*, 2017).

3.3 Antidiabetic effects

Diabetes mellitus is a chronic metabolic disorder characterized by elevated blood glucose levels due to insulin resistance or insufficient insulin production. Spices and herbs have been recognized for their potential antidiabetic effects, primarily through their ability to enhance insulin sensitivity, regulate glucose metabolism and reduce oxidative stress and inflammation associated with diabetes. Cinnamon, a well-studied spice, contains bioactive compounds that

improve insulin sensitivity, lower blood glucose levels and enhance glucose uptake by cells. Turmeric, with its active compound, curcumin, has been shown to improve insulin sensitivity and reduce blood glucose levels by modulating signaling pathways involved in insulin signaling and inflammation. Ginger, with its active components like gingerol and shogaol, has hypoglycemic effects, improving insulin sensitivity, reducing blood glucose levels and lower HbA1c. Fenugreek seeds, with their soluble fiber and saponins, can help lower blood glucose levels, improve insulin sensitivity, reduce postprandial glucose levels and enhance glucose tolerance. Black pepper, with its active compound, piperine, has been found to improve insulin sensitivity and lower blood glucose levels, enhancing the bioavailability of other antidiabetic compounds and regulating glucose metabolism (Pereira *et al.*, 2019).

Bitter melon, *Aloe vera, Gymnema sylvestre*, Ginseng and Holy basil are natural remedies that can help lower blood glucose levels and improve glycemic control in diabetic patients. Bitter melon contains bioactive compounds like charantin, vicine and polypeptide-p, which have insulin-like effects and help lower blood glucose levels (Kumaree and Prasansuklab, 2023). *Aloe vera* has been shown to lower blood glucose levels and improve glycemic control in diabetic patients. *Gymnema sylvestre* contains gymnemic acids that inhibit glucose absorption in the intestines and stimulate insulin production. Ginseng, particularly Korean ginseng, contains ginsenosides that improve insulin sensitivity, lower blood glucose levels and enhance glucose metabolism. Holy basil, or tulsi, contains eugenol and other bioactive compounds that help regulate blood glucose levels and improve insulin sensitivity (Kumar and Srivastava, 2018).

The mechanisms of antidiabetic action of these herbs include enhancing insulin sensitivity, regulating glucose metabolism, reducing oxidative stress and reducing inflammation. These natural remedies also have anti-inflammatory effects, which help improve insulin function and reduce diabetes-related complications (Pereira *et al.*, 2019). Antidiabetic properties of spices and herbs can improve glycemic control, reduce diabetes complications, enhance insulin sensitivity and support weight management. These natural remedies can help manage blood glucose levels, reduce the risk of developing type 2 diabetes and improve insulin sensitivity, leading to better glucose uptake and utilization. They can also aid in weight management, which is crucial for controlling blood glucose levels and reducing the risk of diabetes. However, it is essential to consult with healthcare professionals before making significant changes to dietary practices, especially for individuals with diabetes. Incorporating these natural remedies into a balanced diet can complement conventional diabetes management strategies, supporting overall glycemic control and enhancing health (Bi *et al.*, 2017). Certain flavonoids help in regulating blood sugar levels by enhancing insulin sensitivity and reducing glucose absorption in the intestines, making them beneficial for managing diabetes.

4. Preclinical studies using spices and herbs

4.1 *In vitro* studies

The objective is to evaluate the biological activity of spices and herbs at the cellular level, focusing on their effects on cell viability, proliferation, and molecular signaling pathways. Numerous studies have demonstrated that certain spices and herbs exhibit potent antioxidant properties. For instance, curcumin (from turmeric) and resveratrol (from grapes) have been shown to mitigate oxidative stress by scavenging free radicals and upregulating antioxidant enzymes, which are critical in the prevention of neurodegenerative diseases and cardiovascular conditions. These compounds also modulate the Nrf2 signaling pathway, which plays a pivotal role in cellular defense mechanisms against oxidative damage.

In addition to their antioxidant capabilities, several spices exhibit significant anti-inflammatory properties. Gingerol, the active component of ginger, and allicin from garlic have been found to suppress the production of pro-inflammatory cytokines like TNF-α, IL-1β, and IL-6, which are implicated in chronic inflammatory conditions such as rheumatoid arthritis and inflammatory bowel disease (Singh *et al*., 2019). These spices act through the inhibition of NF-κB and COX-2 pathways, key regulators of inflammation.

Essential oils from herbs like oregano and thyme also demonstrate remarkable antimicrobial activity. Studies have shown that the carvacrol and thymol in these oils disrupt bacterial cell membranes, leading to increased permeability and eventual cell death. Their effectiveness has been observed against drug-resistant strains of *Staphylococcus aureus, Escherichia coli*, and *Pseudomonas aeruginosa* (Nostro *et al*., 2018), suggesting potential applications in addressing antimicrobial resistance.

Moreover, several spices and herbs, including curcumin, capsaicin (from chili peppers), and berberine (from barberry), have demonstrated cytotoxic effects against various cancer cell lines, including breast, colon, and prostate cancers. These compounds induce apoptosis *via* the p53, Bax/Bcl-2, and caspase pathways (Aggarwal *et al.,* 2020). Such findings support the potential role of these bioactive compounds in cancer prevention and treatment, either as standalone therapies or in conjunction with conventional treatments like chemotherapy (Gautam *et al.*, 2019).

4.2 Animal models

The objective is to assess the effectiveness, safety and pharmacokinetics of spices and herbs in living organisms. Studies have shown that certain herbs, such as curcumin, have anticancer properties, such as inhibiting tumor growth and metastasis. Cinnamon and fenugreek have shown improvements in glucose tolerance and insulin sensitivity, suggesting potential benefits for diabetes management. *Ginkgo biloba* and rosemary have been shown to protect against neurodegenerative diseases, while ginger and boswellia have been shown to reduce inflammation and pain in arthritis models (Gautam *et al.*, 2019).

4.3 Mechanistic insights

The biological mechanisms through which spices and herbs exert their effects. Curcumin, a spice, modifies signaling pathways involved in inflammation and oxidative stress, while piperine enhances nutrient and drug bioavailability by inhibiting metabolic enzymes and efflux transporters. Gingerol, a spice, inhibits COX-2 and lipoxygenase enzymes, providing anti-inflammatory effects and neuroprotective benefits. Resveratrol activates SIRT1, a protein involved in cellular stress responses and aging and modulates pathways related to longevity and metabolism. Finally, garlic allicin exhibits anti-inflammatory and antimicrobial effects through redox status modulation (Choudhary and Yousuf, 2019).

5. Applications in the medicinal industry

5.1 Drug development

Spices and herbs are rich sources of bioactive compounds, which are often identified through preclinical studies before advancing to clinical trials. Curcumin, a polyphenol derived from turmeric, is known for its anti-inflammatory, antioxidant and anticancer properties, which have been used in developing drugs for cancer, Alzheimer's disease and inflammatory conditions (Chaurasia and Bharati, 2022). Resveratrol, found in grapes and red wine, is known for its antiageing and cardioprotective effects, inspiring the development of analogs targeting SIRT1 activation for conditions like metabolic disorders and neurodegenerative diseases. Green tea's EGCG exhibits antioxidant, anticancer and neuroprotective activities and is being explored in drug development for its potential to treat conditions like cancer, obesity and neurodegenerative diseases. Capsaicin, an active component in chili peppers, has been developed into topical drugs for pain relief, particularly in conditions like arthritis and neuropathy. Allicin, an organosulfur compound from garlic, has antimicrobial and anti-inflammatory properties and serves as a lead compound in developing antibacterial and cardiovascular drugs (Patwardhan, 2007).

Nutraceuticals and functional foods derived from spices and herbs have gained significant market traction due to their potential health benefits beyond basic nutrition. Market trends include the growth in health awareness, the focus on natural products, personalized nutrition and regulatory support. Examples of these products include turmeric-based products, green tea extracts, probiotic yogurts, garlic supplements and omega-3 fatty acids found in flaxseeds and chia seeds. Advances in nutrigenomics and personalized medicine are also leading to the development of functional foods tailored to individual health needs and genetic profiles (Chaurasia *et al.*, 2024). The list of major alkaloids present in spices and herbs and their activities (Ahamad *et al.*, 2023; Martha Perez Gutierrez *et al.*, 2013).

Table 2: List of major alkaloids present in spices and herbs and their activities

Alkaloid	Primary action	Uses
Ajmaline	Antiarrhythmic	Primarily used to treat irregular heartbeats; derived from the Rauwolfia plant.
Atropine, Hyoscyamine, Scopolamine	Anticholinergic	Block the action of acetylcholine in the nervous system; used to treat various conditions like bradycardia and motion sickness.
Caffeine	Stimulant, Adenosine receptor antagonist	Commonly found in coffee and tea; enhances alertness and reduces fatigue.
Codeine	Analgesic, Antitussive	Used for mild to moderate pain relief and as a cough suppressant; derived from opium.
Colchicine	Antigout	Treats and prevents gout attacks; derived from the autumn crocus plant.
Emetine	Emetic, Antiprotozoal	Induces vomiting; also used in the treatment of amoebiasis; derived from the Ipecac root.
Ergot Alkaloids	Vasoconstrictor, Uterotonic, Hallucinogenic	Derived from the ergot fungus; used in migraine treatment and to induce labor, but can cause severe side effects.
Morphine	Potent analgesic	Strong pain reliever derived from opium; used in severe pain management.
Nicotine	Stimulant, Nicotinic acetylcholine receptor agonist	Found in tobacco; highly addictive, stimulates the central nervous system.
Physostigmine	Acetylcholinesterase inhibitor	Used in the treatment of glaucoma and as an antidote for anticholinergic poisoning; derived from the Calabar bean.
Quinidine	Antiarrhythmic	Stereoisomer of quinine; used to treat certain types of arrhythmias.
Quinine	Antimalarial, antipyretic	Historically used to treat malaria; derived from the bark of the cinchona tree.
Reserpine	Antihypertensive	Used to manage high blood pressure; derived from the Rauwolfia plant.
Tubocurarine	Muscle relaxant	Causes paralysis by blocking acetylcholine receptors; used in anesthesia.
Vinblastine, Vincristine	Anticancer agents	Inhibit cell division; used in chemotherapy for various types of cancer; derived from the periwinkle plant.
Vincamine	Vasodilator, antihypertensive	Improves blood flow, particularly in the brain; used in treating vascular dementia.
Yohimbine	Stimulant, aphrodisiac	Derived from the bark of the yohimbe tree; used for erectile dysfunction and as a stimulant.

6. Prospects and future directions

Research on spices and herbs is rapidly evolving, with emerging trends such as exploring underutilized plants, multi-target approaches, synergistic combinations, biotechnology and genomics, nanotechnology in bioactive compound delivery, personalized medicine and integration with conventional medicine. Underutilized plants are rich in unique phytochemicals that may offer novel bioactive compounds with therapeutic potential. Multi-target approaches target complex

diseases like cancer, neurodegenerative disorders and metabolic syndrome, offering more effective and less toxic treatment options. Synergistic combinations of different spices, herbs, or their bioactive compounds could enhance therapeutic efficacy, reduce required dosages and minimize side effects. Technological innovations in biotechnology and genomics enable the identification and characterization of bioactive compounds at the molecular level, including the use of omics technologies to understand their effects on biological systems. Nanotechnology is revolutionizing the delivery of bioactive compounds from spices and herbs, addressing challenges such as poor solubility, stability and bioavailability. The global market for products derived from spices and herbs is poised for significant growth due to increasing consumer demand for natural and health-promoting products.

7. Conclusion

The medicinal industry is increasingly recognizing the potential of bioactive compounds from spices and herbs, with preclinical studies consistently demonstrating their efficacy in various therapeutic areas, including anti-inflammatory, antimicrobial, and anticancer treatments. As scientific advancements continue to drive innovation in drug development, these natural products are well-positioned to be translated into clinically viable therapeutics. However, the regulatory landscape for herbal supplements remains complex and often inconsistent across regions, underscoring the need for further standardization, quality control, and clinical validation to ensure safety and efficacy. Additionally, the integration of bioactive compounds into personalized medicine offers promising avenues for tailored treatments with fewer side effects, aligning with the growing demand for holistic and patient-centered healthcare. By combining cutting-edge research in biotechnology with traditional knowledge of natural products, there is potential for a new era of therapeutic solutions.

Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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Citation **S.S. Vasanthkumar, T. Prabhu, S. Shenbagavalli, J. Rajangam, S. Vallal Kannan, and A. Baskaran (2024). Exploring the therapeutic potential of bioactive compounds in spices and herbs: Preclinical evidence and medicinal applications. Ann. Phytomed., 13(2):230-237. http://dx.doi.org/10.54085/ap.2024.13.2.22.**