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A REVIEW ON THE MEDICINAL AND CULINARY SIGNIFICANCE OF INDIAN SPICES AND CONDIMENTS

Satish Chandra[1]*, Meena[2], Kaonen Haider[2] and Rupali Sharma[3],

[1]Department of Zoology, School of Science Vivek University, Bijnor – 246701 Uttar Pradesh, India
[2]Department of Botany, School of Science Vivek University, Bijnor – 246701 Uttar Pradesh, India
[3]Biocontrol Laboratory, R.H G. P College Kashipur, (Udham Singh Nager), 244713, Uttarakhand, India
Email: satishchandra.sci@vivekuniversity.ac.in
Orchid ID: 0000-0005-0374-0041

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ABSTRACT

Spices and condiments, long valued for their distinctive flavors and aromas, have gained growing scientific attention for their diverse phytochemical profiles and associated health benefits. These natural products are rich in bioactive compounds such as alkaloids, flavonoids, phenolics, terpenoids, tannins, and essential oils, which contribute not only to their sensory appeal but also to their potent antioxidant, antimicrobial, anti-inflammatory, and therapeutic activities. This review highlights the phytochemical composition, biological significance, toxicological considerations, and emerging applications of commonly used spices including turmeric, black pepper, clove, and cinnamon. Despite their widespread use and general safety, concerns remain regarding contamination with heavy metals, pesticide residues, adulteration, and potential allergic reactions. Advances in analytical chemistry, nanotechnology, and food biotechnology have significantly enhanced the extraction efficiency, formulation stability, and bioavailability of spice-derived compounds. Furthermore, ensuring product safety and efficacy necessitates strict quality control, sustainable cultivation, and adherence to regulatory standards. Overall, spices and condiments represent a crucial link between traditional dietary practices and modern nutraceutical research, offering immense potential for the development of functional foods and preventive healthcare solutions. This comprehensive review provides valuable insights for researchers, nutritionists, and policymakers aiming to promote the safe, sustainable, and innovative utilization of spice phytochemicals

Keywords: Spices, Condiments, Phytochemicals, Bioactive compounds, Antioxidant activity, Nutraceuticals, Toxicology.

INTRODUCTION

Essential ingredients in cooking, spices and condiments act as food additives that enhance taste, aroma, and stimulation rather than nutrition. Their primary functions include improving food flavor and palatability, breaking dietary monotony, and stimulating the senses of taste and secretion. Spices are typically used during food preparation, whereas condiments are often added at the dining table to complement and enhance the cuisine. Unlike herbs—which are derived from leaves, flowers, or stems—spices are usually obtained from other plant parts such as seeds, roots, bark, or fruits. They may be used in powdered, dried, or fresh forms; for instance, fresh spices like ginger possess a stronger flavor but spoil more quickly, while dried spices have a longer shelf life. Depending on culinary requirements, spices such as fennel, mustard, and turmeric are often used either whole or ground. Beyond cooking, spices have applications in traditional medicine, religious rituals, and the cosmetics and fragrance industries. For example, vanilla is widely used in the production of flavours and fragrances. For more than 7,000 years, spices have inspired exploration, colonialism, and cultural exchange, significantly shaping global trade and civilisation. India remains the world's largest producer—accounting for nearly 75% of total spice output—demonstrating its deep cultural and historical connection to the spice trade.

For centuries, spices and condiments have been integral to human diets and societies, serving as trade commodities, medicinal resources, and culinary enhancers. According to García-Casal, Peña-Rosas, and Gómez-Malavé (2016), spices are plant-derived materials—such as seeds, roots, bark, fruits, and rhizomes—commonly used in dried form to impart flavor, color, and aroma to food. In contrast, condiments are usually table-side preparations like sauces, chutneys, or pickles, added primarily to enhance flavor after cooking. Although both contribute little nutritional value, they are vital components of global cuisines that stimulate the senses (Pandey et al. 2022). Spices and condiments are plant-based compounds valued for their ability to enhance the flavor, color, and aroma of food while also providing therapeutic and preservative benefits. Although historically important in food preservation and trade, modern research highlights their biochemical and pharmacological properties (Khatri et al. 2023). Rich in flavonoids, alkaloids, phenolics, and volatile oils, spices play key roles in both sensory enhancement and health promotion. In recent years, the spice industry has experienced renewed growth due to increasing consumer demand for natural, health-promoting, and clean-label products (Fortune Business Insights, 2024).

Many spices contain phytochemicals with proven biological activity. Curcuminoids in turmeric (Curcuma longa) possess anti-inflammatory and antioxidant properties, while clove (Syzygium aromaticum) and cinnamon (Cinnamomum verum) have high phenolic content and strong radical-scavenging potential (Singh et al. 2022). These substances act as natural antioxidants that reduce oxidative stress and may lower the risk of chronic diseases such as diabetes and cardiovascular disorders (Sulieman et al. 2023). According to Khatri et al. (2023), compounds such as capsaicin in chili and piperine in black pepper also enhance nutrient absorption and regulate digestive enzyme activity.

Recent research has demonstrated the role of spice polyphenols in regulating gut microbiota, indicating prebiotic-like effects that support overall health (Singh et al. 2022). Further controlled clinical studies are required to determine precise mechanisms and optimal dietary dosages. Due to their antimicrobial properties, the food industry increasingly views spices and essential oils as natural alternatives to synthetic preservatives. Essential oils from clove, oregano, thyme, and rosemary—rich in eugenol, thymol, and carvacrol—exhibit bactericidal and fungicidal activity against foodborne pathogens such as *Escherichia coli*, *Listeria monocytogenes*, and *Aspergillus niger* (Sulieman et al. 2023). Incorporating these natural extracts into food packaging and preservation systems offers significant potential to extend shelf life while maintaining safety (Singh et al. 2022). However, practical application may be limited by their strong sensory effects, necessitating encapsulation techniques and optimized formulations (Khatri et al. 2023).

Global consumer interest in ethnic cuisines and functional foods continues to drive the rapid expansion of the spice and seasoning market. According to Fortune Business Insights (2024), rising demand for organic and single-origin spices is expected to sustain growth in the global industry, valued at over USD 25 billion in 2023. Traditional spice industries in Asia and Africa are evolving through advances in post-harvest technology, nutraceutical applications, and processed spice blends (Sulieman et al. 2023). Despite these benefits, spices remain vulnerable to contamination and adulteration during production and trade. Common issues include microbial contamination, pesticide residues, and adulteration with non-food materials. In 2024, regulatory agencies found that nearly 12% of tested Indian spice samples exceeded permissible residue limits, emphasizing the urgent need for improved traceability and quality control (Reuters, 2024).

(A) Historical and Cultural Context

Spices have profoundly influenced human civilization. The ancient spice trade shaped commercial routes linking Europe, the Middle East, and Asia. For thousands of years, spices have played vital roles in Ayurveda, religious ceremonies, and daily Indian cuisine (Tripathi, 2024). The European pursuit of Indian spices such as cloves, cinnamon, and black pepper fueled exploration, colonialism, and global trade (Oxford Research Encyclopedias, n.d.). India continues to dominate global spice production, accounting for about 75% of worldwide output (Pandey et al. 2022). Archaeological evidence suggests that spices such as cinnamon, pepper, and turmeric were used for culinary, medicinal, and ceremonial purposes by ancient civilizations in Mesopotamia, Egypt, China, and the Indus Valley (Freedman, 2008). In ancient Egypt, cumin and coriander symbolized purity and preservation and were used in embalming and religious rites (Dalby, 2021). Ayurvedic texts like the *Charaka Samhita* describe the medicinal importance of cardamom, turmeric, and black pepper, underlining their role in health and nutrition (Kumar et al. 2021).

During the Middle Ages, the spice trade became a major driver of global commerce and exploration. Arab merchants dominated the spice routes between Asia and Europe, transporting cloves, nutmeg, and cinnamon from the Maluku Islands—also known as the "Spice Islands" (Freedman, 2008). The immense value of these spices motivated explorers such as Christopher Columbus and Vasco da Gama to embark on voyages that reshaped world geography and established colonial empires (Dalby, 2021). Historically, spices symbolized wealth, luxury, and hospitality. Culinary traditions across the Middle East, Mediterranean, and India—reflected in blends like *garam masala*, *baharat*, and *za'atar*—demonstrate the cultural depth of spice use (Kumar et al. 2021). Today, spices continue to represent prosperity, purity, and wellness in religious festivals and rituals. Thus, spices hold enduring cultural and historical significance that extends far beyond their culinary value—they embody a legacy of trade, identity, and human connection.

(B) Culinary and Functional Role

Spices enhance the sensory appeal of food by providing flavor, aroma, and variety. They are typically added during cooking, while condiments are used during consumption (García-Casal et al. 2016). Many cuisines utilize spices such as garlic, ginger, and turmeric not only for taste but also for their recognized health benefits. Spices are also used in religious rituals, cosmetics, and perfumery, reflecting their broad cultural significance (Pandey et al. 2022). By combining sweet, spicy, sour, and bitter components, spices balance taste profiles and stimulate appetite (Peter, 2021). Beyond flavor enhancement, certain spices such as cumin, ginger, and turmeric help prevent microbial growth and oxidative rancidity, thereby improving food stability and safety (Sulieman et al., 2023). Culinary systems across the world reflect deep traditional knowledge, with regional spice blends like Middle Eastern *za'atar*, Chinese five-spice, and Indian *garam masala* illustrating local identity and adaptation to climate (Dalby, 2021).

Functionally, spices contain bioactive compounds such as eugenol, piperine, and curcumin that aid digestion and exhibit anti-inflammatory and antioxidant properties (Singh et al. 2022). Their integration into daily diets bridges gastronomy and traditional medicine, enhancing not only sensory pleasure but also health benefits. Therefore, in both traditional and modern cuisines, spices and condiments serve as natural functional ingredients and cultural flavoring agents, linking food, health, and heritage.

(C) Medicinal and Health Perspectives

Spices have long been associated with therapeutic applications. In Ayurveda, they are recommended for digestive, respiratory, and metabolic disorders. Modern pharmacological studies confirm that bioactive constituents such as piperine in black pepper, allicin in garlic, and curcumin in turmeric exhibit anti-inflammatory, antibacterial, and antioxidant properties (Pandey et al. 2022; García-Casal et al. 2016). However, most health claims are derived from traditional knowledge and in vitro research, with limited large-scale human trials to validate them (García-Casal et al. 2016). Spices and condiments are rich in bioactive compounds such as terpenoids, alkaloids, and polyphenols, providing antidiabetic, antimicrobial, and anti-inflammatory effects (Khatri et al. 2023). Curcumin from turmeric (Curcuma longa) has shown significant efficacy in reducing oxidative stress and inflammation—key factors in chronic diseases like arthritis and cardiovascular disorders (Gupta et al. 2022). Likewise, organosulfur compounds in garlic (Allium sativum) help regulate cholesterol and blood pressure (Peter, 2021). Regular consumption of spices has been linked to improved gut health and immune modulation (Singh et al. 2022). Compounds such as piperine and capsaicin also enhance nutrient bioavailability and digestion (Khatri et al. 2023). Thus, spices play an emerging role in preventive health and functional nutrition beyond culinary use.

(D) Current Trends and Availability

With globalization, the demand for and availability of spices have expanded significantly. Spices are available in fresh, dried, or ground forms; while fresh spices like mint and ginger offer stronger flavors, they are more perishable and less accessible (Pandey et al. 2022). Advances in food technology and international trade now ensure year-round access to high-quality spices (Tripathi, 2024). According to Fortune Business Insights (2024), the global spice and seasoning market—valued at over USD 25 billion in 2023—is expected to grow further due to rising consumer demand for natural, functional, and sustainably sourced products. The popularity of ready-to-eat foods and blended spice mixes has also surged owing to globalization and changing eating habits (Sulieman et al. 2023). Technological innovations such as vacuum packaging, encapsulation, and cryogenic grinding have improved flavor retention, shelf life, and safety (Peter, 2021).

However, challenges such as adulteration, pesticide residues, and microbial contamination have prompted stricter international standards and traceability systems (Reuters, 2024). With robust trade networks and digital marketplaces, consumers worldwide now enjoy unprecedented access to diverse spice varieties. Overall, current trends reflect a dynamic shift in the spice industry toward innovation, quality assurance, and sustainability.

2. CLASSIFICATION OF SPICES AND CONDIMENTS

Throughout history, condiments and spice blends have held aesthetic, medicinal, and preservative significance in addition to their culinary uses. India—one of the largest producers and exporters of spices—has developed several classification systems based on plant characteristics, economic importance, climatic requirements, seasonal growth, and biochemical composition. However, due to overlaps between categories, no single classification system is entirely comprehensive (Peter, 2006; Parthasarathy et al. 2008).

(a) classification based on plant parts used

The most common classification is based on the plant part utilized as the spice. Various morphological components are used, including seeds (cumin, coriander, mustard), bulbs (garlic, onion), bark (cinnamon), fruits (cardamom, chili), leaves (mint, curry leaf), rhizomes (ginger, turmeric), pods (vanilla, tamarind), and floral structures (saffron, clove). This system is particularly useful as it relates directly to processing and applications in both culinary and medicinal contexts (Sivaraman & Devasahayam, 2010).

(B) classification based on economic importance

From an economic standpoint, major spices such as cardamom, black pepper, chili, turmeric, and ginger are distinguished from minor spices like coriander, cumin, fennel, clove, cinnamon, and nutmeg. Major spices dominate global trade, contributing 75–90% of total spice revenue, while minor spices, though regionally important, diversify the spice economy. Minor spices can be further categorized into seed spices, bulbous spices, aromatic spices, leafy spices, and acidulant tree spices (Ravindran, 2017).

(C) Classification Based on Climatic Requirements

Spices can also be classified according to climatic adaptability. Tropical spices such as cinnamon, ginger, turmeric, and black pepper thrive in warm, humid conditions. Temperate spices like saffron and caraway grow better in cooler climates, whereas subtropical spices such as cumin, coriander, fennel, onion, and garlic prefer regions with seasonal variations (Parthasarathy et al. 2008). This classification is particularly relevant for crop planning, breeding programs, and sustainable agricultural practices under changing climate conditions.

(D) Classification Based on Origin and Flavor Compounds

This phytochemical classification groups spices into aromatic (cardamom, coriander, cinnamon), pungent (chili, ginger, mustard), phenolic (clove, allspice), and coloring (turmeric, saffron, paprika) types. It reflects the volatile oils, alkaloids, phenols, and pigments

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responsible for distinctive sensory and medicinal properties (Sowbhagya & Purnima, 2010). This approach is vital in pharmacognosy and the flavor and fragrance industries.

(E) CLASSIFICATION BASED ON SEASON OF GROWTH

Agronomically, spices are classified as annuals (coriander, cumin, fennel), biennials (onion, parsley), or perennials (black pepper, nutmeg, clove). This classification influences crop rotation, field management, and germplasm conservation (Peter, 2006).

3-MATRIX OF PLANT PARTS USED IN SPICES & CONDIMENTS-

S.No	Common Name	Botanical Name	Root	Stem	Leaf	Seed	Flower	Fruit	Rhizome	Bark	Stigma	Whole Plant
01	Asafoetida	*Ferula asafetida*	+	-	-	-	-	-	+	-	-	-
02	Black Pepper	Piper nigrum	-	-	-	-	-	+	-	-	-	-
03	Caraway	Elettaria cardamomum	-	-	-	+	-	-	-	-	-	-
04	Cardamom	*Elettaria cardamomum*	-	-	-	+	-	-	-	-	-	-
05	Chillies	*Capsicum frutescens*	-	-	-	-	-	+	-	-	-	-
06	Cinnamon	*Cinnamomum zeylanicum*	-	-	+	-	-	-	-	+	-	-
07	Curry Leaf	*Murraya koenigii*	-	-	+	-	-	-	-	-	-	-
08	Fennel	*Foeniculum vulgare*	-	-	-	+	-	-	-	-	-	-
09	Fenugreek	*Trigonella foenum-graecum*	-	-	-	+	-	-	-	-	-	-
10	Garlic	*Allium sativum*	-	-	-	+	-	-	+	-	-	-
11	Ginger	*Zingiber officinale*	-	-	-	-	-	-	+	-	-	-
12	Mint	*Mentha arvensis*	-	-	+	-	-	-	-	-	-	-
13	Mustard	*Brassica nigra*	-	-	-	+	-	-	-	-	-	-
14	Onion	*Allium cepa*	-	-	-	-	-	-	+	-	-	-
15	Saffron	*Crocus sativus*	-	-	-	-	-	-	-	-	+	-
16	Saffron	*Tamarindus indica*	-	-	-	-	-	+	-	-	-	-
17	Tejpat	*Cinnamomum tamala*	-	-	+	-	-	-	-	-	-	-
18	Turmeric	*Curcuma domestica*	-	-	-	-	-	-	-	+	-	-
19	Cloves	*Eugenia caryophyllata*	-	-	-	-	-	+	-	-	-	-
20	Coriander	*Coriandrum sativum*	-	-	-	-	-	-	-	+	-	-

+ Presents, **-** Absents

Table -1: The detailed of the Plant Parts Used in Spices & Condiments

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4- USES AND BENEFITS OF SPICES AND CONDIMENTS FOR HUMANS

Spices	Benefits
Asafoetida	It is a successful treatment for a number of gastrointestinal disorders. Because of its anti-inflammatory, antiviral, and antibacterial properties, it aids in the relief of respiratory conditions such as bronchitis, dry cough, asthma, and others.
Black and white paper	Black pepper is a weight-loss aid. It aids in digestion and reduces the risk of cancer by cleansing the body. White pepper helps regulate blood pressure and lessen gas, or flatulence.
Caraway	It assists in lowering dyspepsia, or indigestion, and chronic inflammation. It assists in maintaining your weight.
Cardamom	It aids in the management of foul breath and digestive issues. You may manage your diabetes by chewing a whole cardamom.
Chilli	Chilli contains antioxidants that help lower cholesterol. It assists in burning calories.
Cinnamon	It lowers blood cholesterol and encourages the body to produce insulin naturally.
Cloves	One useful remedy for toothaches and sore gums is clove oil. Additionally, it is a good treatment for colds, coughs, fevers, digestive issues, and chest aches.
Coriander	It can be used topically to rheumatism and sore joints. Additionally, it helps treat hay fever, allergies, digestive issues, and sore throat.
Curry leaf	It helps in the treatment of dysentery, diarrhea, diabetes, morning sickness, and nausea by adding curry leaves to your meals. It also helps in losing weight.
Fennel	It helps in digestive problems. It helps to control heart rate and blood pressure. It also helps in the treatment of many diseases like anemia, asthma etc.
Fenugreek	Helps regulate blood sugar levels and diabetes. It increases milk supply for nursing mothers, improves menstruation cramps, lowers blood pressure, and increases testosterone.
Garlic	It is useful for coping with cough and cold. It also has antibiotic properties.
Ginger	It helps in digestive problems. It is beneficial for coping with cough and cold.
Mint	Mint is an excellent treatment for stomach issues. It lessens the severity of cold symptoms. It facilitates stress management.
Mustard	Mustard seeds contain antioxidant and anti-inflammatory properties that help in relieving pain in the gum, bones, and teeth. It helps in digestion, headaches and migraines.
Onion	Onions are an excellent source of antioxidants. It helps in diabetes, cancer and heart diseases.
Saffron	It helps to cope with skin diseases. It is a good remedy for cough, cold and asthma.
Tamarind	It helps in diarrhea, constipation, fever, and malaria. It also help in weight loss.
Tejpat	Triglycerides and bad cholesterol (LDL-cholesterol) are decreased by it. It raises HDL cholesterol, or good cholesterol, levels. Thus, it aids in cardiac conditions. aids in better digestion.
Turmeric	Turmeric powder can be used for healing cuts and wounds. It helps in skin problems. It also makes coping with diabetes easier.

Table -2: The detailed of the Benefits of spices and condiments for Humans.

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5-PHYTOCHEMICAL CONSTITUENTS OF SPICES

Spice(Scientific Name)	Major Phytochemical Constituents	Phytochemical Class	Major Biological Activities
Turmeric (*Curcuma longa)*	Curcumin, Demethoxycurcumin, Bis-demethoxycurcumin, Turmerones	Polyphenols, Sesquiterpenes	Antioxidant, Anti-inflammatory, Anticancer
Ginger (*Zingiber officinale)*	6-Gingerol, 8-Gingerol, 6-Shogaol, Zingerone, Zingiberene	Phenolics, Terpenoids	Antioxidant, Anti-inflammatory, Antiemetic, Gastro protective
Clove (*Syzygium aromaticum*)	Eugenol, Eugenyl acetate, β-Caryophyllene	Phenylpropanoids, Volatile oils	Antioxidant, Antimicrobial, Analgesic
Cinnamon (*Cinnamomum spp.)*	Cinnamaldehyde, Cinnamic acid, Eugenol	Phenylpropanoids	Antioxidant, Anti-diabetic, Anti-inflammatory
Cinnamon *(Cinnamomum spp.)*	Cinnamaldehyde, Cinnamic acid, Eugenol	Phenylpropanoids	Antioxidant, Anti-diabetic, Anti-inflammatory
Black Pepper (*Piper nigrum)*	Piperine, Limonene, Pinene, β-Caryophyllene	Alkaloids, Monoterpenes	Bioavailability enhancer, Antioxidant, Anti-inflammatory
Garlic *(Allium sativum)*	Allicin, Ajoene, Diallyl disulfide, Diallyl trisulfide	Organosulfur compounds	Antimicrobial, Cardioprotective, Anticancer
Chili (*Capsicum spp.)*	Capsaicin, Dihydrocapsaicin, Nordihydrocapsaicin	Alkaloids (Capsaicinoids)	Analgesic, Thermo genic, Antioxidant
Cumin (*Cuminum cyminum*)	Cuminaldehyde, β-Pinene, γ-Terpinene	Aldehydes, Terpenes	Antimicrobial, Digestive, Antioxidant
Cardamom (*Elettaria cardamomum*)	1,8-Cineole, α-Terpinyl acetate, Linalool	Terpenoids	Digestive stimulant, Antioxidant, Antimicrobial
Fenugreek (*Trigonella foenum-graecum*)	Diosgenin, Saponins, Flavonoids	Steroidal saponins, Polyphenols	Hypoglycemic, Antioxidant, Anti-inflammatory

Table -3: The details of the phytochemical constituents of Spices.

6. TOXICOLOGICAL AND SAFETY ASPECTS OF COMMON CULINARY SPICES

Spices have long been considered safe for culinary use, but toxicological issues may arise from factors such as pharmacokinetic interactions, adulteration or contamination, excessive supplementation, and the intrinsic toxicity of certain constituents.

(A) Curcumin / Turmeric

Human studies and regulatory assessments confirm that oral intake of curcuminoids is generally well tolerated, with only mild gastrointestinal discomfort reported at high supplemental doses. Turmeric is widely regarded as safe at food-level consumption and has been used extensively in clinical trials (Sharifi-Rad et al., 2020; Committee on Toxicity [COT], 2024). However, adulteration and contamination—such as the addition of lead chromate for enhanced color—pose significant safety concerns. These issues have prompted regulatory agencies to issue warnings and to strengthen surveillance (COT, 2024; Zeng et al., 2022).

(B) Piperine

Piperine, the principal alkaloid in black pepper, is safe at typical dietary levels but can raise safety and drug-interaction concerns when used in concentrated or isolated forms. Animal and human pharmacokinetic studies indicate that piperine significantly increases the bioavailability of co-administered compounds by inhibiting certain metabolic enzymes and transporters. This can alter drug exposure and potentially affect clinical safety (Ziegenhagen et al. 2021; Lin et al. 2024). Consequently, toxicology and regulatory reviews recommend caution when adding piperine to pharmaceutical or high-dose nutraceutical formulations.

(C) Eugenol

Eugenol (found in clove oil) and similar phenylpropanoids possess strong antioxidant and antibacterial activities but may be associated with altered liver enzyme levels and, in the case of impurities such as methyl eugenol, genotoxic effects at high exposures. Current EFSA assessments indicate that normal food and feed levels of eugenol and related essential oils do not pose safety concerns for consumers. Nonetheless, vigilance regarding impurities and occupational exposure remains important (EFSA, 2025).

(D) Organosulfur Compounds

Garlic contains organosulfur compounds (e.g., diallyl sulfides, allicin) that are considered safe in culinary use. However, at higher supplemental doses, clinical trials report mild side effects such as gastric irritation, odor, dizziness, or transient hemodynamic changes (El-Saadony et al. 2024; Savairam, 2023). While long-term toxicity appears low, further research is needed to characterize chronic exposure risks and potential species-specific effects observed in animal models.

(E) Capsaicinoids

Capsaicinoids, including capsaicin, are generally safe when consumed through the diet. Clinical studies of topical capsaicin for pain management confirm its acceptable safety profile at recommended concentrations. However, topical or concentrated formulations may cause local irritation, burning sensations, or—under excessive exposure—systemic effects such as nausea or vomiting (Petran et al. 2024).

In summary, the toxicological profile of spices depends on their concentration, formulation, and mode of use (culinary versus concentrated supplement). Comprehensive toxicology testing of concentrated extracts and novel delivery systems remains essential to ensure that enhanced bioactivity does not compromise safety. Key research and regulatory priorities include:

1. Strict surveillance for adulterants and contaminants (e.g., heavy metals, synthetic dyes).
2. Systematic evaluation of potential drug interactions when bioavailability modulators like piperine are co-administered.
3. Development of standardized testing frameworks for high-potency spice derivatives (Pancholi et al., 2021; Ziegenhagen et al., 2021).

7. CHALLENGES AND FUTURE PROSPECTS

Despite strong evidence supporting the nutritional, therapeutic, and biocontrol potential of spices and their phytochemicals, several challenges hinder their optimal utilization in the food, pharmaceutical, and agricultural sectors.A major limitation lies in the **variation of chemical composition** resulting from environmental conditions, genotype, cultivation practices, processing, and storage. These differences affect the efficacy, stability, and safety of bioactive compounds such as curcumin, eugenol, piperine, and capsaicin (Sharifi-Rad et al. 2020; Singh et al. 2023). Establishing standardized protocols for extraction, purification, and characterization is therefore essential to ensure reproducible quality and biological outcomes.

Another critical challenge is the **low stability and bioavailability** of certain phytochemicals. Compounds such as curcumin and allicin degrade rapidly under heat, light, and alkaline pH, leading to poor systemic absorption (Patra et al. 2021). Advanced delivery systems—such as emulsions,

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microencapsulation, and nanocarriers—have shown promise in enhancing solubility, stability, and sustained release, though scalability and cost-effectiveness remain areas of active research (Ahmad et al. 2022; Yadav et al. 2024). Regulatory and toxicological barriers also constrain the widespread commercialization of spice-derived bioactives. Market adoption is slowed by the absence of harmonized international standards, limited human safety data, and incomplete toxicology databases (Zeng et al. 2022; EFSA, 2025). Contamination with heavy metals, artificial dyes, and unauthorized additives continues to pose public health risks, necessitating robust traceability systems and global quality compliance (COT, 2024).

In agriculture, essential oils and secondary metabolites from spices show strong antimicrobial and insecticidal potential. However, large-scale applications are limited by phytotoxicity, environmental instability, and inconsistent pest-control efficacy (Kumar et al. 2023; Singh & Pandey, 2022). Innovative strategies such as nanoemulsions, biopolymer coatings, and synergistic formulations with microbial biocontrol agents may help overcome these limitations and facilitate sustainable pest management. Looking forward, **omics-driven research**, **precision formulation**, and **green technologies** offer exciting prospects for spice bioactives. Metabolomics, genomics, and machine learning approaches enable the identification of chemotypes with superior stability and efficacy (Ramakrishnan et al. 2024). Biotechnological interventions—including synthetic biology, plant tissue culture, and CRISPR-based metabolic engineering—could further enhance the sustainable production of high-value secondary metabolites (Patra et al. 2021; Yadav et al. 2024).

Ultimately, a **multidisciplinary approach** integrating food science, pharmacology, toxicology, agronomy, and policy development is essential to fully realize the potential of spices in medicine, biopesticides, and functional foods. Addressing challenges of safety, bioavailability, and standardization will not only strengthen international trade but also support rural livelihoods and promote climate-resilient agriculture (Kumar et al. 2023; EFSA, 2025)

Conclusion

At the intersection of traditional medicine, pharmacology, and gastronomy, spices and condiments occupy a unique and indispensable role. Once valued primarily for their flavor and aroma, they are now recognized as reservoirs of bioactive compounds with significant biological functions. Substances such as curcumin, eugenol, piperine, cinnamaldehyde, capsaicin, and allicin provide strong defenses against oxidative stress, microbial infections, and inflammatory disorders.The phytochemical diversity of spices demonstrates that their therapeutic properties arise from synergistic interactions among multiple metabolites rather than a single active compound. Advanced analytical tools such as GC–MS, HPLC, and metabolomics have improved standardization and authentication methods, thereby enhancing product safety and quality. However, maintaining phytochemical stability during processing, storage, and cooking remains an ongoing challenge.

Although most spices are safe when consumed in moderation, issues such as adulteration, pesticide residues, mycotoxin contamination, and unauthorized medicinal use warrant careful regulatory oversight. Establishing permissible exposure limits and conducting regular monitoring are essential to ensure consumer safety. The inherently low bioavailability of many phytochemicals also calls for innovative formulation strategies—including encapsulation and nanocarrier systems—to enhance absorption and therapeutic efficacy.

The potential of spice-derived bioactives in pharmaceuticals, nutraceuticals, and functional foods is immense. Standardized spice extracts with well-characterized phytochemical profiles could transform preventive nutrition and integrative medicine. Advances in biotechnology and crop genetics offer additional opportunities to enhance spice productivity, quality, and phytochemical content under sustainable agricultural systems.

Promoting fair trade, organic farming, and biodiversity conservation will ensure that the global spice trade remains both economically viable and environmentally responsible. In conclusion, spices and condiments represent far more than mere culinary adjuncts—they are dynamic natural resources that bridge traditional wisdom and modern science. Their rich phytochemical repertoire continues to inspire the search for safer, multifunctional, and sustainable compounds that advance human health and food security. With appropriate regulation, standardization, and technological innovation, the spice industry can become a cornerstone of sustainable health and wellness in the 21st century.

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