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Indian spices and condiments: Traditional knowledge, phytochemistry, food applications, therapeutic potential and emerging industrial perspectives

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Abstract
Spices and condiments are integral to Indian food culture, traditional healthcare, food preservation, commerce, and biodiversity-based livelihoods. India is a major producer, consumer, processor and exporter of spices, with commercially important crops including turmeric (*Curcuma longa*), black pepper (*Piper nigrum*), ginger (*Zingiber officinale*), cardamom (*Elettaria cardamomum*), cinnamon (*Cinnamomum* spp.), clove (*Syzygium aromaticum*), cumin (*Cuminum cyminum*), coriander (*Coriandrum sativum*), fenugreek (*Trigonella foenum-graecum*), chilli (*Capsicum annuum*), garlic (Allium sativum) and mustard (*Brassica* spp.). The culinary and biological properties of these plants are associated with diverse phytochemicals, including polyphenols, flavonoids, terpenoids, alkaloids, curcuminoids, organosulfur compounds, essential oils and oleoresins. This narrative review integrates historical and traditional knowledge with contemporary information on phytochemistry, functional food properties, preservation, pharmacological potential, nutraceutical applications and industrial utilization of Indian spices. Particular emphasis is given to antioxidant and antimicrobial functions, bioavailability enhancement, green extraction, nanoencapsulation, active packaging and emerging delivery systems. The review also considers food-safety hazards, adulteration, contamination, phytochemical variability, regulatory requirements and the need for stronger clinical validation. Available evidence indicates substantial potential for spice-derived ingredients in functional foods, nutraceuticals, pharmaceuticals, cosmetics and sustainable food technologies; however, many therapeutic claims require confirmation through standardized preparations and well-designed human studies. Future research should integrate traditional knowledge with metabolomics, genomics, food biotechnology, climate-resilient cultivation, quality-control systems and evidence-based clinical research. Indian spices therefore represent multifunctional biological resources with important nutritional, cultural, economic and technological value.

Keywords: Indian spices, condiments, traditional knowledge, phytochemicals, essential oils, food preservation

Introduction

Spices and condiments have been indispensable components of human civilization for more than five millennia, contributing not only to the sensory qualities of food but also to medicine, religious rituals, preservation, trade, and cultural identity (Anderson, 2023; Ravindran, 2023) [20, 45]. Archaeological and historical evidence indicates that the use of spices dates back to ancient civilizations in the Indus Valley, Mesopotamia, Egypt, China, Greece, and Rome, where aromatic plants were valued as luxury commodities, medicines, preservatives, perfumes, and embalming agents (Pruthi, 1998; Auboyer, 1961; Anderson, 2023) [3, 4, 42]. The ancient spice trade profoundly influenced global exploration, commerce, and colonization, motivating voyages by explorers such as Vasco da Gama and Christopher Columbus in search of direct sea routes to the spice-producing regions of Asia (Anderson, 2023; Ravindran, 2023) [3].

India has traditionally been recognized as the "Land of Spices" because of its exceptional agro-climatic diversity and long history of cultivating aromatic and medicinal plants. The country is the world's largest producer, consumer, and exporter of spices, producing more than 75 commercially important spice crops that contribute substantially to agricultural income, food security, export earnings, and rural livelihoods. Indian spices such as black pepper (*Piper nigrum*), turmeric (*Curcuma longa*), ginger (*Zingiber officinale*), cardamom (*Elettaria cardamomum*), cumin (*Cuminum cyminum*), coriander (Coriandrum sativum), fenugreek (*Trigonella foenum-graecum*), cinnamon (*Cinnamomum verum*), clove (*Syzygium aromaticum*), chilli (*Capsicum annuum*), garlic (*Allium sativum*), and mustard (*Brassica* spp.) are globally renowned for their unique aroma, flavor, quality, and medicinal significance (Peter, 2012; Ravindran, 2023; FAO, 2024; Spices Board India, 2024) [3, 15, 40, 53]. India also continues to play a leading role in the development of international Codex standards for spices and culinary herbs, strengthening global food quality and trade standards.

The terms spices and condiments encompass a wide variety of plant-derived products obtained from seeds, fruits, bark, roots, rhizomes, flower buds, stigmas, leaves, bulbs, and stems that impart flavor, aroma, pungency, color, and preservative properties to foods (Pruthi, 1998; Peter, 2012) [40, 42]. Their characteristic sensory attributes arise from a complex mixture of bioactive phytochemicals, including essential oils, oleoresins, alkaloids, flavonoids, phenolic acids, terpenoids, carotenoids, sulfur-containing compounds, glycosides, tannins, and other secondary metabolites. These compounds not only determine culinary quality but also exhibit remarkable biological activities that have attracted increasing scientific attention (Srinivasan, 2005, 2014; Peter, 2012) [40, 54, 55].

Traditional Indian healthcare systems such as Ayurveda, Siddha, Unani, and folk medicine have extensively employed spices for disease prevention and treatment for thousands of years. Turmeric has long been used as an anti-inflammatory and wound-healing agent; ginger for digestive disorders and nausea; garlic for cardiovascular diseases; black pepper as a bioavailability enhancer; cinnamon for glycemic control; cloves as analgesic and antimicrobial agents; and fenugreek for diabetes management. Contemporary pharmacological and clinical investigations increasingly validate these traditional applications through studies demonstrating antioxidant, antimicrobial, antiviral, antifungal, anti-inflammatory, antidiabetic, antihyperlipidemic, hepatoprotective, cardioprotective, neuroprotective, immunomodulatory, gastroprotective, anticancer, and chemopreventive properties of spice-derived phytochemicals (Billing & Sherman, 1998; Kaefer & Milner, 2008; Srinivasan, 2014; Yashin *et al*., 2017; Gidwani *et al*., 2022; Dhale, 2022; Dhale & Patil, 2012; Kaur *et al*., 2025) [7, 29, 30, 39, 55, 65, 66].

Growing consumer awareness regarding healthy diets and the demand for clean-label foods have accelerated research on spices as functional foods and nutraceutical ingredients. Natural antioxidants and antimicrobial compounds isolated from spices are increasingly replacing synthetic food additives because of their ability to inhibit microbial growth, delay lipid oxidation, enhance shelf life, improve sensory quality, and provide additional health benefits. Consequently, spice-derived bioactive compounds are widely utilized in the food, pharmaceutical, cosmetic, nutraceutical, and biotechnology industries (Tapsell *et al*., 2006; Srinivasan, 2014; Gidwani *et al*., 2022; Kaur *et al*., 2025) [21, 30, 55, 58]. Recent advances in metabolomics, genomics, nanotechnology, green extraction techniques, and food biotechnology have further expanded the applications of spices in precision nutrition and evidence-based healthcare (Mandal *et al*., 2023; Gupta *et al*., 2024; Mojica *et al*., 2026) [23, 37, 45].

Economically, the spice sector represents one of India's most valuable agricultural industries. The establishment of the Indian Institute of Spices Research (IISR), the Spices Board of India, and India's leadership in the Codex Committee on Spices and Culinary Herbs have significantly contributed to improved cultivation practices, quality assurance, value addition, export promotion, and international standardization. Despite these achievements, challenges including adulteration, contamination, variability in phytochemical composition, climate change, quality standardization, traceability, and clinical validation continue to limit the wider therapeutic utilization of spices (WHO, 2022; Codex Alimentarius Commission, 2025 [11]; Ministry of Commerce and Industry, Government of India, 2024; World Bank, 2024) [53, 63].

Therefore, this review comprehensively summarizes the historical evolution, traditional knowledge, phytochemistry, food applications, pharmacological activities, therapeutic potential, industrial importance, and recent scientific advances related to Indian spices and condiments. It further highlights current challenges, quality assurance, sustainability, and future research opportunities for promoting evidence-based utilization of Indian spices in food systems, nutraceuticals, pharmaceuticals, and global healthcare.

History and Global Importance of Spices

The history of spices is closely intertwined with the development of human civilization, international trade, cultural exchange, and the evolution of traditional medicine. Archaeological evidence suggests that spices were used as early as 5000–3000 BCE, when ancient civilizations of the Indus Valley, Mesopotamia, Egypt, and China utilized aromatic plants for food preservation, religious ceremonies, embalming, perfumery, and medicinal purposes (Rosengarten, 1969; Dalby, 2000; Anderson, 2023) [3, 12, 47]. Ancient Egyptian records reveal the extensive use of cinnamon, cassia, cumin, coriander, garlic, and onion during mummification and religious rituals, while Chinese medical literature documented the therapeutic applications of ginger, cinnamon, and star anise more than 4,000 years ago (Rosengarten, 1969; Dalby, 2000) [12, 47].

India has occupied a central position in the global history of spices for over five millennia. The Vedic literature, including the Rigveda, Atharvaveda, and Charaka Samhita, describes numerous spices such as turmeric (*Curcuma longa*), black pepper (*Piper nigrum*), ginger (*Zingiber officinale*), cumin (*Cuminum cyminum*), coriander (*Coriandrum sativum*), cardamom (*Elettaria cardamomum*), and garlic (*Allium sativum*) for culinary, medicinal, and spiritual purposes (Auboyer, 1961; Achaya, 1998; Ravindran, 2023) [1, 4, 45]. Ayurvedic texts recognized spices as essential components of health promotion, emphasizing their digestive, antimicrobial, anti-inflammatory, and rejuvenating properties (Charaka, 1994; Sushruta, 2001) [9, 57].

During antiquity, Indian spices became highly prized commodities in international commerce. Trade routes connecting India with Mesopotamia, Persia, Egypt, Greece, and the Roman Empire facilitated the exchange of pepper, cinnamon, cardamom, turmeric, and other valuable spices. Roman historian Pliny the Elder noted the enormous demand for Indian pepper in Europe, where spices symbolized wealth, prestige, and luxury (Pliny the Elder, 1991; Dalby, 2000) [12, 41]. Arab merchants dominated the spice trade between the 7th and 15th centuries by controlling maritime routes linking India with the Mediterranean and Europe (Keay, 2000; Anderson, 2023) [3, 31].

The quest for direct access to India's spice-producing regions became a major driving force behind the Age of Exploration. Portuguese navigator Vasco da Gama reached Calicut (Kozhikode), India, in 1498, opening a direct maritime route between Europe and Asia and transforming global commerce (Keay, 2000; Anderson, 2023) [3, 31]. Subsequently, Portuguese, Dutch, French, and British colonial powers competed fiercely to control the lucrative spice trade, leading to the establishment of trading companies, colonial settlements, and extensive maritime networks. Christopher Columbus's westward voyage in 1492, originally intended to reach the spice-producing East Indies, ultimately resulted in the European discovery of the Americas, illustrating the profound influence of spices on world history (Rosengarten, 1969; Dalby, 2000) [12, 47].

Historically, spices served multiple functions beyond flavor enhancement. Before refrigeration, spices such as clove (*Syzygium aromaticum*), cinnamon (*Cinnamomum verum*), garlic, mustard, and black pepper were widely employed as natural preservatives because of their antimicrobial and antioxidant properties. They were also incorporated into perfumes, cosmetics, embalming materials, incense, and traditional medicines across Asia, Africa, Europe, and the Middle East (Pruthi, 1998; Peter, 2012; Srinivasan, 2005) [40, 42, 54]. Their high commercial value made spices comparable to precious metals and gemstones, significantly influencing international trade, taxation, and economic development during the medieval period (Rosengarten, 1969; Anderson, 2023) [3, 47].

In the modern era, spices have become indispensable commodities in the global food industry. More than 109 spices are recognized internationally, with India cultivating over 75 commercially important species under diverse agro-climatic conditions (Peter, 2012; Spices Board India, 2024) [40, 53]. India remains the world's largest producer, consumer, and exporter of spices, accounting for a substantial share of global spice production and supplying more than 180 countries with products including pepper, turmeric, ginger, chilli, cumin, coriander, fennel, fenugreek, cardamom, and nutmeg (FAO, 2024; Spices Board India, 2024) [53]. The Indian spice sector contributes significantly to agricultural GDP, employment generation, rural livelihoods, and foreign exchange earnings through exports of whole spices, essential oils, oleoresins, and value-added spice products.

Scientific interest in spices has expanded enormously over the past three decades owing to growing evidence of their health-promoting properties. Advances in phytochemistry, metabolomics, molecular biology, and food science have identified numerous bioactive compounds, including polyphenols, flavonoids, terpenoids, alkaloids, carotenoids, sulfur compounds, essential oils, and oleoresins that exhibit antioxidant, antimicrobial, anti-inflammatory, antidiabetic, cardioprotective, neuroprotective, immunomodulatory, and anticancer activities (Srinivasan, 2014; Yashin *et al*., 2017; Gidwani *et al*., 2022; Kaur *et al*., 2025) [30, 55, 65, 66]. Consequently, spices are increasingly recognized as functional foods and nutraceutical ingredients, with applications extending beyond traditional culinary uses into pharmaceuticals, cosmetics, biotechnology, and preventive healthcare (Sharma *et al*., 2025; Singh *et al*., 2023) [50, 52].

Global organizations including the Food and Agriculture Organization (FAO), the World Health Organization (WHO), the Codex Alimentarius Commission, and the International Organization for Standardization (ISO) have established standards and guidelines to ensure the quality, authenticity, safety, and international trade of spices. Moreover, consumer demand for natural preservatives, clean-label foods, sustainable agriculture, and plant-based bioactive compounds has stimulated research on innovative processing technologies, encapsulation, green extraction methods, and value-added spice products (WHO, 2022; Codex Alimentarius Commission, 2025) [11]. These developments underscore the continuing economic, nutritional, medicinal, and cultural significance of spices in the twenty-first century (International Organization for Standardization, 2024 [27]; Food Safety and Standards Authority of India, 2023) [20].

Overall, the historical evolution of spices—from sacred medicinal plants and luxury trade commodities to globally important functional food ingredients—highlights their enduring contribution to human civilization. Their unique combination of culinary value, therapeutic potential, economic importance, and cultural heritage ensures that spices will remain integral to sustainable food systems, public health, and global commerce for generations to come.

Classification of Spices and Condiments

Spices and condiments are classified according to their botanical origin, plant part used, flavor characteristics, chemical constituents, culinary applications, and commercial importance. This classification facilitates their identification, quality assessment, industrial utilization, and pharmacological evaluation (Pruthi, 1998; Peter, 2012; Ravindran, 2023) [40, 42, 45].

1. Classification Based on Plant Parts

The most widely accepted botanical classification groups spices according to the plant organ utilized.

Seeds: Coriander (*Coriandrum sativum*), cumin (*Cuminum cyminum*), fennel (*Foeniculum vulgare*), fenugreek (*Trigonella foenum-graecum*), mustard (*Brassic*a spp.), dill (*Anethum graveolens*), and celery (*Apium graveolens*) (Pruthi, 1998; Peter, 2012) [40, 42].

Fruits: Black pepper (*Piper nigrum*), chilli (*Capsicum annuum*), paprika, allspice (*Pimenta dioica*), vanilla (*Vanilla planifolia*), star anise (*Illicium verum*), and cardamom (*Elettaria cardamomum*) (Ravindran, 2002; Peter, 2012) [40, 43].

Rhizomes: Turmeric (*Curcuma longa*), ginger (*Zingiber officinale*), galangal (*Alpinia galanga*), and zedoary (*Curcuma zedoaria*) (Govindarajan, 1982; Ravindran, 2007) [22, 44].

Bark: Cinnamon (*Cinnamomum verum*) and cassia (Cinnamomum cassia) (Peter, 2012) [40].
Flower buds: Clove (*Syzygium aromaticum*) (Pruthi, 1998) [42].

Stigmas: Saffron (*Crocus sativus*) (Peter, 2012) [40].
Leaves: Bay leaf (*Cinnamomum tamala*), curry leaves (*Murraya koenigii*), mint (*Mentha* spp.), basil (*Ocimum basilicum*), and oregano (*Origanum vulgare*) (Srinivasan, 2005) [54].

Bulbs: Garlic (*Allium sativum*) and onion (*Allium cepa*) (Kaefer & Milner, 2008) [29].

2. Classification Based on Culinary Function

Spices are also categorized as flavoring spices, pungent spices, aromatic spices, coloring spices, preservative spices, and medicinal spices depending on their primary culinary and functional roles (Pruthi, 1998; Peter, 2012) [40, 42].

3. Classification Based on Economic Importance

The International Organization for Standardization (ISO), Codex Alimentarius Commission, and the Spices Board of India recognize more than 100 commercially traded spices worldwide. India cultivates over 75 economically important spice crops, accounting for approximately half of the global spice trade by volume (Spices Board India, 2024; FAO, 2024 [53]; International Organization for Standardization, 2024) [27].

Chemical Constituents and Bioactive Compounds

The remarkable biological properties of spices are attributed to their diverse secondary metabolites. These phytochemicals influence aroma, taste, color, preservation, and pharmacological activities (Srinivasan, 2014; Peter, 2012) [40, 55].

1. Polyphenols and Phenolic Acids

Polyphenols constitute one of the largest groups of antioxidant compounds found in spices. Curcumin from turmeric, rosmarinic acid from herbs, ferulic acid, caffeic acid, gallic acid, chlorogenic acid, and ellagic acid exhibit potent antioxidant, anti-inflammatory, anticancer, and cardioprotective activities (Srinivasan, 2014; Yashin *et al*., 2017; Kaur *et al*., 2025) [30, 55, 65].

2. Flavonoids

Flavonoids such as quercetin, kaempferol, rutin, luteolin, apigenin, catechin, and hesperidin contribute significantly to free radical scavenging, vascular protection, and immune regulation (Yashin *et al*., 2017; Gidwani *et al*., 2022) [65, 66].

3. Terpenoids

Terpenoids constitute the principal components of essential oils. Monoterpenes (limonene, pinene, cineole, linalool), sesquiterpenes (β-caryophyllene), and diterpenes impart characteristic aroma while exhibiting antimicrobial, anti-inflammatory, and antioxidant activities (Peter, 2012; Ravindran, 2023) [40, 45].

4. Alkaloids

Piperine in black pepper and capsaicin in chilli are important alkaloids responsible for pungency. Piperine enhances intestinal absorption and improves the bioavailability of several drugs and phytochemicals, whereas capsaicin exhibits analgesic, anti-obesity, anticancer, and anti-inflammatory properties (Govindarajan, 1982; Srinivasan, 2005) [22, 54].

5. Organosulfur Compounds

Garlic and onion contain sulfur-containing compounds including allicin, diallyl sulfides, ajoene, and S-allyl cysteine, which possess antimicrobial, antihypertensive, cardioprotective, hypolipidemic, and anticancer activities (Kaefer & Milner, 2008; Zhang *et al*., 2024) [29, 67].

6. Curcuminoids

Turmeric contains curcumin, demethoxycurcumin, and bisdemethoxycurcumin, collectively known as curcuminoids. These compounds exhibit broad pharmacological activities including antioxidant, anti-inflammatory, neuroprotective, hepatoprotective, antimicrobial, and anticancer effects (Ravindran, 2007; Hewlings & Kalman, 2021) [26, 44].

7. Other Bioactive Molecules

Other biologically active constituents include carotenoids, lignans, coumarins, tannins, glycosides, saponins, polysaccharides, vitamins, minerals, and dietary fibers that contribute to the nutraceutical value of spices (Srinivasan, 2014; Gidwani *et al*., 2022) [21, 55].

Essential Oils and Oleoresins

Essential oils and oleoresins are concentrated natural products responsible for the characteristic aroma, flavor, and biological activities of spices. They are extensively utilized in the food, pharmaceutical, cosmetic, perfumery, and nutraceutical industries (Pruthi, 1998; Peter, 2012) [40, 42].

1. Essential Oils

Essential oils are volatile aromatic mixtures obtained primarily by steam distillation or hydrodistillation. Their major constituents include terpenes, terpenoids, alcohols, aldehydes, ketones, esters, ethers, and phenolic compounds (Bakkali *et al*., 2008) [6].

Major spice essential oils include

Table 1: Representative major constituents of essential oils from selected spices

Spice	Components in Essential oils
1. Allspice	Eugenol; 1,8-cineol; humulene, α-phellandrene
2. Basil, sweet	Linalool; 1,8-cineol; methyl chavicol, eugenol
3. Cardamom	1,8-cineol, linalool; limonene, α-terpineol acetate
4. Dill leaf	Carvone, limonene, dihydrocarvone, α-phellandrene
5. Epazote	Ascaridol, limonene, *p*-cymene, myrcene, α-pinene
6. Fennel	Anethole, fenchone, limonene, α-phellandrene
7. Ginger	Zingiberene, curcumene, farnescene, linalool, borneol
8. Juniper	α-pinene, β-pinene, thujene, sabinene, borneol
9. Kari leaf	Sabinene, α-pinene, β-caryophyllene
10. Lemongrass	Citral, myrcene, geranyl acetate, linalool
11. Marjoram	*cis*-sabinene, α-terpinene, terpinene 4-ol, linalool
12. Nutmeg	Sabinene, α-pinene, limonene, 1,8-cineol
13. Oregano	Terpinene 4-ol, α-terpinene, *cis*-sabinene
14. Pepper, black	Sabinene, β-pinene, α-pinene, limonene, 1,8-cineol
15. Rosemary	1,8-cineol, borneol, camphor, bornyl acetate
16. Star anise	Anethole, α-pinene, β-phellandrene, limonene
17. Turmeric	Turmerone, dihydroturmerone, sabinene, 1,8-cineol
18. Zeodary	Germacrone-4, furanodienone, curzerenone, camphor

These volatile compounds exhibit strong antioxidant, antimicrobial, antiviral, insecticidal, antifungal, anti-inflammatory, and preservative activities, making them valuable natural alternatives to synthetic additives (Bakkali *et al*., 2008; Patil and Dhale, 2012; Burt, 2004; Kaur *et al*., 2025; Ahmed *et al*., 2024; Chen *et al*., 2023; Dhale & Patil, 2024) [6, 8, 10, 15, 30, 39].

2. Oleoresins

Oleoresins are solvent-extracted concentrates containing both volatile essential oils and non-volatile resinous compounds. Compared with whole spices, oleoresins provide standardized flavor, enhanced stability, ease of handling, longer shelf life, and improved consistency in industrial food formulations (Pruthi, 1998) [42].

Commercially important oleoresins include turmeric oleoresin (curcuminoids), paprika oleoresin (capsanthin), chilli oleoresin (capsaicinoids), black pepper oleoresin (piperine), ginger oleoresin (gingerols and shogaols), clove oleoresin (eugenol), cumin oleoresin (cuminaldehyde), and coriander oleoresin (linalool). These products are widely incorporated into processed foods, beverages, meat products, confectionery, pharmaceuticals, nutraceuticals, cosmetics, and functional food formulations (Peter, 2012; Gidwani *et al*., 2022; Roy *et al*., 2025) [21, 40, 48].

Recent advances in green extraction technologies, including supercritical CO_2 extraction, microwave-assisted extraction, ultrasound-assisted extraction, enzyme-assisted extraction, and nanoencapsulation, have significantly improved the yield, purity, stability, and bioavailability of spice essential oils and oleoresins while minimizing solvent residues and environmental impact (Kaur *et al*., 2025; Babu, 2024; Kumar *et al*., 2024) [5, 30, 32].

Functional Properties of Spices and Condiments

Spices and condiments are multifunctional plant-derived products that contribute not only to the sensory characteristics of foods but also to nutrition, preservation, and human health. Their biological activities are primarily attributed to a wide range of bioactive phytochemicals, including polyphenols, flavonoids, terpenoids, alkaloids, sulfur-containing compounds, essential oils, and oleoresins (Pruthi, 1998; Peter, 2012; Srinivasan, 2014) [40, 42, 55]. In recent years, increasing consumer demand for natural food ingredients has accelerated research on spices as functional foods and nutraceuticals. Their antioxidant, antimicrobial, anti-inflammatory, and preservative properties have positioned spices as sustainable alternatives to synthetic food additives in the food industry (Tapsell *et al*., 2006; Gidwani *et al*., 2022; Kaur *et al*., 2025) [21, 30, 58].

1. Flavor and Aroma

The most recognized function of spices is their ability to impart distinctive flavor, aroma, color, and pungency to foods. These sensory properties arise from complex mixtures of volatile and non-volatile phytochemicals present in different plant parts, including seeds, fruits, bark, rhizomes, flower buds, and leaves (Peter, 2012; Ravindran, 2023) [40, 45].

Volatile essential oils are the primary contributors to aroma, whereas non-volatile compounds such as alkaloids, phenolics, and oleoresins are largely responsible for taste and pungency. For example, piperine imparts the characteristic pungency of black pepper (Piper nigrum), capsaicin provides the hot sensation of chilli (*Capsicum annuum*), curcumin contributes the bright yellow color of turmeric (*Curcuma longa*), eugenol is responsible for the warm aroma of clove (*Syzygium aromaticum*), cinnamaldehyde gives cinnamon (*Cinnamomum verum*) its sweet-spicy fragrance, while zingiberene, gingerols, and shogaols contribute to the distinctive flavor of ginger (*Zingiber officinale*) (Govindarajan, 1982; Ravindran, 2002; Ravindran, 2007; Peter, 2012) [22, 40, 43, 44].

Modern analytical techniques such as gas chromatography–mass spectrometry (GC–MS), high-performance liquid chromatography (HPLC), and metabolomic profiling have identified hundreds of volatile constituents responsible for the unique sensory profiles of spices. Terpenes, terpenoids, aldehydes, ketones, alcohols, esters, sulfur compounds, and phenolic derivatives collectively determine aroma intensity, flavor complexity, and consumer acceptability (Bakkali *et al*., 2008; Peter, 2012) [6, 40].

Beyond improving palatability, spices stimulate salivary secretion, gastric juice production, digestive enzyme activity, and appetite, thereby enhancing digestion and nutrient utilization (Srinivasan, 2005; Tapsell *et al*., 2006) [54, 58]. The synergistic interaction among different spice constituents also contributes to the characteristic flavor of traditional Indian cuisines and processed foods.

2. Natural Food Preservatives

One of the oldest and most significant functions of spices is their role as natural food preservatives. Long before the advent of refrigeration, spices were employed to extend the shelf life of foods by inhibiting microbial growth and delaying oxidative deterioration (Pruthi, 1998; Dalby, 2000) [12, 42].

Essential oils extracted from spices possess broad-spectrum antimicrobial activity against numerous foodborne pathogens, including Escherichia coli, Salmonella enterica, Listeria monocytogenes, Staphylococcus aureus, Bacillus cereus, Campylobacter jejuni, and various spoilage fungi and yeasts (Burt, 2004; Bakkali *et al*., 2008 [6, 8]; WHO, 2022). The antimicrobial activity primarily results from phenolic compounds such as eugenol, thymol, carvacrol, cinnamaldehyde, allicin, piperine, and curcumin, which disrupt microbial cell membranes, interfere with enzyme systems, inhibit nucleic acid synthesis, and reduce biofilm formation (Billing & Sherman, 1998; Burt, 2004; Ahmed *et al*., 2024) [2, 7, 8].

In addition to antimicrobial activity, spices possess remarkable antioxidant properties that retard lipid oxidation and prevent rancidity in foods. Polyphenols, flavonoids, carotenoids, and phenolic acids effectively scavenge reactive oxygen species (ROS), chelate transition metals, and inhibit oxidative chain reactions responsible for deterioration of fats, oils, meat products, dairy products, and processed foods (Srinivasan, 2014; Yashin *et al*., 2017) [55, 65].

Spices such as rosemary, turmeric, clove, cinnamon, oregano, thyme, garlic, black pepper, cumin, coriander, and ginger have demonstrated excellent preservative efficacy in meat products, edible oils, bakery products, dairy products, seafood, beverages, and minimally processed fruits and vegetables (Burt, 2004; Peter, 2012; Gidwani *et al*., 2022) [8, 21, 40].

The increasing demand for clean-label foods has encouraged the replacement of synthetic preservatives such as butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT), sodium benzoate, and potassium sorbate with natural spice extracts. Modern preservation strategies incorporating spice essential oils, oleoresins, nanoemulsions, edible coatings, biodegradable packaging, and encapsulated phytochemicals have shown considerable promise for improving food safety and extending shelf life while maintaining nutritional quality (Kaur *et al*., 2025; Babu, 2024) [5, 30].

Consequently, spice-derived preservatives are increasingly incorporated into functional foods, ready-to-eat products, nutraceuticals, organic foods, and minimally processed food systems. Their multifunctional roles as flavor enhancers, antioxidants, antimicrobial agents, and natural preservatives make spices indispensable ingredients in sustainable food processing and modern food technology.

3. Antioxidant Properties

Oxidative stress, resulting from the excessive generation of reactive oxygen species (ROS) and reactive nitrogen species (RNS), is implicated in the pathogenesis of numerous chronic diseases, including cardiovascular disorders, diabetes mellitus, cancer, neurodegenerative diseases, chronic inflammation, and premature aging. Dietary antioxidants derived from spices play a crucial role in neutralizing free radicals, preventing oxidative damage to lipids, proteins, nucleic acids, and cellular membranes, thereby promoting human health (Halliwell & Gutteridge, 2021; Srinivasan, 2014; Yashin *et al*., 2017) [24, 55, 65].

Spices are among the richest natural sources of antioxidant phytochemicals. Their antioxidant activity is mainly attributed to polyphenols, flavonoids, phenolic acids, carotenoids, curcuminoids, tannins, alkaloids, and essential oil constituents (Peter, 2012; Kaur *et al*., 2025) [30, 40]. Curcumin from turmeric (*Curcuma longa*), eugenol from clove (*Syzygium aromaticum*), cinnamaldehyde from cinnamon (*Cinnamomum verum*), gingerols from ginger (*Zingiber officinale*), piperine from black pepper (*Piper nigrum*), capsaicin from chilli (*Capsicum annuum*), thymol from thyme (*Thymus vulgaris*), carvacrol from oregano (*Origanum vulgare*), and allicin from garlic (*Allium sativum*) have demonstrated remarkable antioxidant efficacy in experimental and clinical studies (Srinivasan, 2014; Hewlings & Kalman, 2021; Gidwani *et al*., 2022; Lee *et al*., 2024; Yashin *et al*., 2022) [21, 26, 34, 55, 66].

These bioactive compounds exhibit antioxidant activity through multiple mechanisms, including scavenging free radicals, donating hydrogen atoms or electrons, chelating transition metals, inhibiting lipid peroxidation, enhancing endogenous antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx), and modulating redox-sensitive signaling pathways such as Nrf2/ARE (Halliwell & Gutteridge, 2021; Yashin *et al*., 2017) [24, 65].

The antioxidant potential of spices has significant applications in food preservation by delaying oxidation of edible oils, meat products, dairy products, bakery products, seafood, beverages, and processed foods. Consequently, spice extracts are increasingly replacing synthetic antioxidants such as butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT), supporting the development of clean-label foods and natural preservation strategies (Burt, 2004; Gidwani *et al*., 2022; Kaur *et al*., 2025) [8, 21, 30].

4. Food Industry Applications

The food industry extensively utilizes spices and their bioactive constituents because of their multifunctional properties as flavoring agents, coloring agents, preservatives, antioxidants, nutraceutical ingredients, and natural antimicrobial compounds (Pruthi, 1998; Peter, 2012) [40, 42]. Traditionally employed to improve the taste and aroma of foods, spices now play an important role in food processing, packaging, quality enhancement, and shelf-life extension.

Natural colorants such as curcumin, paprika oleoresin, saffron, and annatto are widely incorporated into dairy products, confectionery, beverages, sauces, bakery products, processed meat, and snack foods (Govindarajan, 1982; Peter, 2012) [22, 40]. Essential oils and oleoresins obtained from black pepper, cardamom, clove, cinnamon, cumin, coriander, ginger, fennel, and nutmeg are used extensively in processed foods, ready-to-eat meals, instant seasonings, beverages, confectionery, sauces, soups, pickles, and spice blends.

The antimicrobial and antioxidant properties of spice extracts have facilitated the development of natural food preservation technologies, including edible films, biodegradable packaging materials, nanoemulsions, encapsulated essential oils, and active food packaging systems (Bakkali *et al*., 2008; Babu, 2024) [5, 6]. Green extraction technologies such as supercritical carbon dioxide extraction, ultrasound-assisted extraction, microwave-assisted extraction, enzyme-assisted extraction, and pressurized liquid extraction have significantly improved the quality, stability, and bioavailability of spice-derived ingredients (Kaur *et al*., 2025) [30].

In addition, spice-derived phytochemicals are increasingly incorporated into functional foods, dietary supplements, fortified beverages, nutraceuticals, and personalized nutrition products owing to their scientifically validated health benefits. Current research emphasizes sustainable processing, waste valorization, traceability, quality assurance, geographical indication (GI)-based products, and eco-friendly production systems to enhance the global competitiveness of the spice industry (FAO, 2024; Spices Board India, 2024; Gupta *et al*., 2024; Mojica *et al*., 2026) [2, 37, 53].

Medicinal and Pharmacological Activities

For centuries, spices have occupied a central position in traditional systems of medicine such as Ayurveda, Siddha, Unani, Traditional Chinese Medicine, and numerous indigenous healthcare systems. Modern pharmacological investigations have validated many of these traditional claims by demonstrating diverse biological activities associated with spice-derived phytochemicals (Tapsell *et al*., 2006; Gidwani *et al*., 2022) [21, 58].

The therapeutic potential of spices is attributed to a wide spectrum of secondary metabolites, including polyphenols, flavonoids, terpenoids, alkaloids, curcuminoids, sulfur-containing compounds, carotenoids, and essential oils. These compounds interact with multiple molecular targets involved in inflammation, oxidative stress, apoptosis, immune regulation, glucose metabolism, lipid metabolism, microbial infection, and carcinogenesis (Srinivasan, 2014; Hewlings & Kalman, 2021) [26, 55].

Experimental, epidemiological, and clinical studies have demonstrated that spices possess potent antioxidant, antimicrobial, antiviral, antifungal, anti-inflammatory, antidiabetic, antihyperlipidemic, cardioprotective, hepatoprotective, nephroprotective, neuroprotective, gastroprotective, immunomodulatory, anti-obesity, analgesic, wound-healing, and anticancer activities (Kaefer & Milner, 2008; Gidwani *et al*., 2022; Kaur *et al*., 2025; Latif & Nawaz, 2026; Sharma *et al*., 2025) [21, 29, 30, 33, 50].

Turmeric (*Curcuma longa*) has been extensively investigated for the therapeutic effects of curcumin, which exhibits antioxidant, anti-inflammatory, anticancer, hepatoprotective, neuroprotective, and immunomodulatory activities. Black pepper (*Piper nigrum*) contains piperine, an important bioavailability enhancer that improves the intestinal absorption of curcumin and several pharmaceutical compounds. Ginger (*Zingiber officinale*) possesses antiemetic, anti-inflammatory, gastroprotective, and analgesic activities owing to gingerols and shogaols. Garlic (*Allium sativum*) demonstrates antimicrobial, antihypertensive, cardioprotective, hypolipidemic, and anticancer properties through organosulfur compounds such as allicin. Similarly, cinnamon, cloves, cumin, coriander, fenugreek, cardamom, and chilli have shown promising therapeutic efficacy against metabolic disorders, microbial infections, inflammatory diseases, and oxidative stress-related disorders (Ravindran, 2007; Hewlings & Kalman, 2021; Gidwani *et al*., 2022) (Ding *et al*., 2026; Sadhu *et al*., 2026) [17, 21, 26, 44, 49].

Recent advances in molecular pharmacology, metabolomics, nanotechnology, systems biology, and evidence-based medicine have further strengthened the scientific understanding of spice-derived phytochemicals. Nanoformulations, encapsulated bioactive compounds, and synergistic combinations of phytochemicals are currently being investigated to improve bioavailability, targeted drug delivery, therapeutic efficacy, and clinical outcomes (Kaur *et al*., 2025) [30]. Consequently, spices are increasingly recognized as valuable sources of novel lead molecules for pharmaceutical development, functional foods, nutraceuticals, and preventive healthcare (Wang *et al*., 2026; Zhao *et al*., 2023) [61, 68].

Nutraceutical and Functional Food Applications

The growing prevalence of chronic non-communicable diseases, coupled with increasing consumer awareness regarding healthy lifestyles, has significantly accelerated the demand for nutraceuticals and functional foods derived from natural sources. Among plant-derived ingredients, spices have emerged as valuable nutraceutical resources because they are rich in bioactive phytochemicals with scientifically validated health-promoting properties (Roberfroid, 2000; Wildman, 2007; Gidwani *et al*., 2022) [46, 62, 64]. Their multifunctional composition, including polyphenols, flavonoids, terpenoids, alkaloids, curcuminoids, carotenoids, organosulfur compounds, dietary fiber, vitamins, minerals, essential oils, and oleoresins, makes spices attractive ingredients for functional food formulations (Srinivasan, 2014; Peter, 2012) [40, 55].

A nutraceutical is generally defined as a food or food-derived product that provides health benefits beyond basic nutrition, including the prevention and management of diseases (DeFelice, 1995; Roberfroid, 2000) [13, 46]. Functional foods are conventional or modified foods that contain biologically active compounds capable of improving physiological functions and reducing disease risk (Roberfroid, 2000) [46]. Indian spices satisfy both definitions because they simultaneously enhance food quality and provide numerous pharmacological benefits.

Turmeric (*Curcuma longa*) is one of the most extensively investigated spice-derived nutraceuticals owing to the presence of curcumin, which exhibits antioxidant, anti-inflammatory, anticancer, hepatoprotective, cardioprotective, neuroprotective, antimicrobial, and immunomodulatory activities (Ravindran, 2007; Hewlings & Kalman, 2021) [26, 44]. Piperine from black pepper (*Piper nigrum*) enhances the bioavailability of curcumin and several therapeutic agents by inhibiting hepatic and intestinal metabolism, thereby improving clinical efficacy (Shoba *et al*., 1998) [51]. Ginger (*Zingiber officinale*) contains gingerols and shogaols that demonstrate antiemetic, gastroprotective, anti-inflammatory, antioxidant, and metabolic regulatory activities, while garlic (*Allium sativum*) provides organosulfur compounds with antihypertensive, hypolipidemic, antimicrobial, and cardioprotective effects (Kaefer & Milner, 2008; Hannan *et al*., 2021) [25, 29].

Several spices are increasingly incorporated into functional food products, including herbal beverages, fortified dairy products, probiotic yogurts, cereal bars, bakery products, ready-to-drink beverages, nutritional supplements, functional confectionery, dietary capsules, herbal teas, fermented foods, and sports nutrition formulations (Peter, 2012; Gidwani *et al*., 2022) [21, 40]. Their incorporation enhances not only nutritional value but also sensory characteristics, shelf life, and consumer acceptance.

Recent technological advances such as nanoencapsulation, liposomal delivery systems, microencapsulation, phytosome technology, spray drying, freeze drying, and controlled-release formulations have substantially improved the stability, bioavailability, gastrointestinal absorption, and therapeutic efficacy of spice-derived bioactive compounds (Kaur *et al*., 2025) [30]. Nanocurcumin, nanoemulsified essential oils, encapsulated gingerols, and piperine-based delivery systems are currently under extensive investigation for pharmaceutical and nutraceutical applications (Wang *et al*., 2026; Zhao *et al*., 2023) [17, 68].

Moreover, spice-derived phytochemicals are increasingly recognized as potential preventive agents against obesity, metabolic syndrome, cardiovascular diseases, diabetes mellitus, inflammatory disorders, neurodegenerative diseases, gastrointestinal disorders, microbial infections, and certain cancers. Consequently, spices represent promising candidates for precision nutrition, personalized healthcare, and evidence-based dietary interventions (Srinivasan, 2014; Kaur *et al*., 2025; Diacova *et al*., 2026; Vismaya & Rajini, 2026; Singh *et al*., 2023) [16, 30, 52, 55, 60].

Industrial Applications

The global spice industry represents one of the fastest-growing sectors of the food, pharmaceutical, nutraceutical, cosmetic, and biotechnology industries. Beyond their traditional culinary use, spices serve as valuable industrial raw materials owing to their rich phytochemical composition and multifunctional biological activities (Pruthi, 1998; Peter, 2012) [40, 42].

The food processing industry is the largest consumer of spices and spice-derived ingredients. Whole spices, ground powders, essential oils, oleoresins, spice extracts, seasoning blends, and natural colorants are extensively utilized in processed foods, dairy products, meat products, seafood, bakery items, beverages, confectionery, sauces, soups, pickles, snack foods, ready-to-eat meals, and instant food formulations (Govindarajan, 1982; Peter, 2012) [22, 40]. Curcumin, paprika oleoresin, saffron, and annatto are widely employed as natural food colorants, whereas essential oils from clove, cinnamon, cumin, coriander, ginger, fennel, and black pepper provide desirable flavor and aroma characteristics (Patel *et al*., 2025 [38]; United States Department of Agriculture, 2024) [59].

In the pharmaceutical industry, spice-derived phytochemicals are used in the formulation of herbal medicines, dietary supplements, anti-inflammatory drugs, antimicrobial preparations, topical formulations, oral healthcare products, wound-healing agents, digestive formulations, and immune-supporting products. Curcumin, piperine, eugenol, cinnamaldehyde, allicin, gingerols, and capsaicin have received considerable scientific attention because of their therapeutic potential and safety profiles (Hewlings & Kalman, 2021; Gidwani *et al*., 2022) [21, 26].

The cosmetic and personal care industries utilize essential oils and oleoresins from spices in perfumes, soaps, shampoos, creams, lotions, aromatherapy products, anti-aging formulations, sunscreens, and skin-care products because of their antioxidant, antimicrobial, anti-inflammatory, and fragrance properties (Bakkali *et al*., 2008) [6]. Turmeric, sandalwood, saffron, cinnamon, clove, and cardamom have long been incorporated into traditional and modern cosmetic preparations.

The nutraceutical industry increasingly employs spice extracts in capsules, tablets, herbal teas, functional beverages, sports nutrition products, dietary supplements, and botanical formulations. Standardized extracts containing curcuminoids, piperine, gingerols, capsaicinoids, eugenol, and garlic organosulfur compounds are commercially available worldwide (Wildman, 2007; Gidwani *et al*., 2022) [62, 64].

In agriculture, several spice-derived essential oils exhibit insecticidal, nematicidal, fungicidal, herbicidal, and biopesticidal activities. Botanical pesticides prepared from neem, garlic, chilli, clove, cinnamon, and peppermint oils are increasingly promoted as environmentally friendly alternatives to synthetic pesticides in integrated pest management (IPM) programs (Isman, 2021; Patil & Dhale, 2012) [28, 39].

Recent advances in food engineering and biotechnology have expanded industrial applications through green extraction technologies, supercritical CO_2 extraction, microwave-assisted extraction, ultrasound-assisted extraction, enzyme-assisted extraction, nanoencapsulation, active food packaging, edible coatings, biodegradable polymers, and intelligent packaging systems incorporating spice bioactive compounds (Babu, 2024; Kaur *et al*., 2025) [5, 30]. These technologies improve extraction efficiency, product stability, shelf life, bioavailability, and commercial value while supporting sustainable manufacturing practices (Kumar *et al*., 2024; Patel *et al*., 2025) [32, 38].

The worldwide demand for natural preservatives, clean-label foods, herbal medicines, functional ingredients, and eco-friendly products continues to drive rapid growth in the spice industry. According to the Food and Agriculture Organization and the Spices Board of India, India remains the world's leading producer, consumer, and exporter of spices, contributing substantially to agricultural income, employment generation, rural development, and international trade (FAO, 2024; Spices Board India, 2024) [27, 53]. Continued investment in quality assurance, geographical indication (GI) products, traceability, value addition, sustainable cultivation, and climate-resilient spice production will further strengthen the global competitiveness of the Indian spice sector (Ministry of Commerce and Industry, Government of India, 2024; World Bank, 2024) [53, 63].

Food Safety, Quality Control, Regulatory Considerations and Research Gaps

The increasing use of spices as food ingredients, concentrated extracts and nutraceutical preparations makes quality, authenticity and safety essential considerations. Potential hazards include microbial contamination, mycotoxins, pesticide residues, heavy metals, undeclared additives, adulteration and variability in active constituents. International and national frameworks emphasize microbiological safety, standardized specifications, good manufacturing practices and appropriate labeling for foods and botanical preparations (World Health Organization, 2022; European Food Safety Authority, 2023 [20, 64]; Food Safety and Standards Authority of India, 2023) [20].

Quality evaluation should address botanical identity, purity, moisture content, ash values, volatile-oil profile, marker compounds, microbial load, contaminants and adulterants, together with suitable chromatographic or spectroscopic fingerprinting. Codex and ISO standards provide important international frameworks for spice quality and trade, while Indian regulatory requirements provide the national context for food safety and product compliance (Codex Alimentarius Commission, 2025 [11]; International Organization for Standardization, 2024 [27]; Food Safety and Standards Authority of India, 2023) [20].

A major research limitation is the variability of phytochemical composition caused by genotype, geographical origin, climate, soil, agronomic practice, maturity, processing and storage. Consequently, evidence obtained from purified compounds or concentrated extracts should not automatically be extrapolated to culinary doses of whole spices. Future studies should prioritize authenticated plant material, standardized extracts, validated analytical methods, dose-response studies, pharmacokinetic evaluation and adequately powered human clinical trials. Such approaches are particularly important for translating traditional claims into evidence-based applications (Gidwani *et al*., 2022; Latif & Nawaz, 2026; Kaur *et al*., 2025) [21, 30, 33].

Sustainability is equally important because increasing demand for spices may place pressure on agricultural resources, biodiversity and post-harvest systems. Climate-resilient cultivation, integrated pest management, traceability, geographical indication-based value addition, reduction of post-harvest losses and responsible utilization of processing by-products can improve both environmental and economic outcomes. Botanical pesticides and other spice-derived products also warrant evaluation within integrated pest-management systems (Isman, 2021 [28]; Food and Agriculture Organization of the United Nations, 2024; Spices Board India, 2024) [19].

Conclusion

Indian spices and condiments have served as indispensable components of human civilization for thousands of years, extending far beyond their traditional role as flavoring agents. Historical records, traditional medical systems, and modern scientific investigations collectively demonstrate that spices are rich reservoirs of biologically active phytochemicals with significant nutritional, therapeutic, industrial, and economic value. The presence of polyphenols, flavonoids, terpenoids, alkaloids, curcuminoids, organosulfur compounds, essential oils, and oleoresins contributes to their diverse pharmacological properties, including antioxidant, antimicrobial, anti-inflammatory, antidiabetic, cardioprotective, neuroprotective, hepatoprotective, immunomodulatory, and anticancer activities (Pruthi, 1998; Srinivasan, 2014; Gidwani *et al*., 2022; Kaur *et al*., 2025) [21, 30, 42, 55].

Beyond their medicinal significance, spices have become integral components of the modern food industry as natural flavoring agents, preservatives, antioxidants, colorants, and functional ingredients. Their increasing incorporation into nutraceuticals, functional foods, pharmaceuticals, cosmetics, and active food-packaging systems reflects the growing global demand for natural, safe, and sustainable products. Advances in phytochemical profiling, metabolomics, nanotechnology, green extraction technologies, encapsulation, and biotechnology have substantially enhanced the stability, bioavailability, and commercial applications of spice-derived bioactive compounds, thereby expanding their potential in preventive healthcare and evidence-based medicine (Bakkali *et al*., 2008; Hewlings & Kalman, 2021; Babu, 2024) (Babu, 2024; Mandal *et al*., 2023) [5, 6, 26, 35].

India continues to occupy a leading position in global spice production, consumption, and export, contributing significantly to food security, agricultural sustainability, rural livelihoods, and international trade. Nevertheless, challenges such as adulteration, contamination, variability in phytochemical composition, climate change, post-harvest losses, quality standardization, regulatory harmonization, and limited clinical validation remain significant barriers to maximizing the therapeutic and commercial potential of Indian spices. Addressing these challenges requires multidisciplinary collaboration among botanists, food scientists, pharmacologists, biotechnologists, clinicians, regulatory agencies, and the spice industry to establish standardized cultivation practices, advanced quality-control systems, traceability mechanisms, and evidence-based clinical research (FAO, 2024; Spices Board India, 2024; Codex Alimentarius Commission, 2025) [11, 34, 53].

Future research should prioritize comprehensive metabolomic characterization, genomic-assisted crop improvement, sustainable cultivation practices, climate-resilient spice production, green extraction technologies, nanoformulation-based delivery systems, randomized clinical trials, and precision nutrition approaches. Integrating traditional knowledge with modern scientific methodologies will facilitate the discovery of novel bioactive compounds and innovative therapeutic applications while ensuring the conservation and sustainable utilization of India's rich spice biodiversity.

In conclusion, Indian spices and condiments represent a unique convergence of culinary heritage, traditional medicine, modern pharmacology, and industrial innovation. Their multifaceted biological activities, nutritional benefits, and broad industrial applications underscore their importance as valuable natural resources for improving human health, enhancing food quality, promoting sustainable agriculture, and supporting the global bioeconomy. Continued scientific research, technological advancement, and international collaboration will further strengthen the role of Indian spices as key contributors to functional foods, nutraceuticals, pharmaceuticals, and sustainable healthcare systems in the twenty-first century.

Conflict of Interest

The author declares that there is no conflict of interest associated with this review article.

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