International Journal of Food Science and Nutrition
www.foodsciencejournal.com
E-ISSN: 2455-4898
Received: 18-09-2026, Accepted: 18-10-2026, Published: 02-11-2026
Volume 11, Issue 4, 2026, Page No. 92-97

Bioactive compounds, pharmacological profile and cultural heritage of ten principal Indian spices

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DOI: https://doi.org/10.66856/ijfsn.2026.11.4.11196

Abstract
India is a leading producer and exporter of many spice crops with significant cultural, economic, agricultural, and medicinal importance. This paper examines ten popular Indian spices: black pepper (*Piper nigrum*), cumin (*Cuminum cyminum*), turmeric (*Curcuma longa*), coriander (*Coriandrum sativum*), clove (*Syzygium aromaticum*), fenugreek (*Trigonella foenum-graecum*), cinnamon (*Cinnamomum verum*), green cardamom (*Elettaria cardamomum*), thyme (*Trachyspermum ammi*) and fennel (*Foeniculum vulgare*). These crops are primarily grown in India's major geographic regions, including Gujarat, Rajasthan, Kerala, Karnataka, Tamil Nadu, and Maharashtra. A wide range of bioactive secondary metabolites, such as essential volatile oils, monoterpenes, sesquiterpenes, phenylpropanoids, alkaloids, flavonoids, and phenolic acids, are revealed by phytochemical analyses. Their unique sensory qualities and wide therapeutic potential are supported by important active substances as piperine, cuminaldehyde, curcumin, linalool, eugenol, cinnamaldehyde, eucalyptol, and thymol. These spices have potent antioxidant, anti-inflammatory, antibacterial, antidiabetic, gastroprotective, cardioprotective, and neuroprotective qualities, according to pharmacological analyses. These plants' profound ethnobotanical roots in South Asian cooking customs, Ayurvedic medicine, maternity care, agricultural biopesticides, and sacred ceremonies confirm their ongoing importance in world industry and health.

Keywords: Antimicrobial, antioxidant, black pepper, curcumin, ethnobotany, phytochemicals and spices

Introduction

Indian spices serve as both powerful medicinal agents and culinary flavour enhancers, making them the cornerstone of the Ayurvedic medical system. Food is regarded as the main source of medicine in Ayurveda. The majority of kitchen spices function as medications or "bio-enhancers" that treat illnesses, regulate the body's doshas (Pitta, Kapha, and Vata), and greatly boost the effectiveness of other herbal remedies. The active ingredients in these spices alter membrane permeability, suppress harmful metabolic enzymes, and lessen oxidative stress, according to research that increasingly supports these antiquated assertions. Bioactive plant components found in Indian spices have important anti-inflammatory, antioxidant, and metabolic health advantages. Strong active phytochemicals like curcumin, gingerols, cinnamaldehyde, eugenol, and piperine are found in important botanical agents like turmeric (*Curcuma longa*), cloves (*Syzygium aromaticum*), ginger (*Zingiber officinale*), black pepper (*Piper nigrum*), fenugreek (*Trigonella foenum-graecum*), cardamom (*Elettaria cardamomum*) and saffron (*Cuminum cyminum*). When taken as a whole, these substances promote the activity of digestive enzymes, improve the absorption of nutrients, improve glycemic control, lower LDL cholesterol, and control blood pressure. Additionally, they support cardiovascular protection, pain alleviation, and mood stabilization, underscoring the promise of traditional Indian culinary spices as successful dietary therapies for the prevention of chronic illness and overall wellbeing. This paper examines ten popular Indian spices:

Black Pepper (*Piper nigrum*)

One of India's most significant spice crops, black pepper is a blooming vine grown for its dried fruit, which is used as a condiment and spice is frequently referred to as the "King of Spices." It belongs to family Piperaceae (Pepper family). India is one of the world's top producers and exporters of black pepper (*Piper nigrum* L.), which is mostly grown in the Western Ghats' wet tropical regions. The great majority of India's production comes from Kerala and Karnataka. Parts of Maharashtra, Goa, the Andaman and Nicobar Islands, the Nilgiris, Tamil Nadu, and increasingly Northeastern provinces like Assam and Meghalaya. Because it contains piperine, which gives it its strong flavour and therapeutic qualities, it is prized for its use in culinary flavouring, medicine, and food preservation. Alkaloids, terpenes, and phenolic chemicals are the rich secondary metabolites found in *Piper nigrum.* Piperine is the main strong alkaloid that gives black pepper its harsh flavor; depending on processing, it usually makes up 3.4% to 5.9% or more of the dry weight. Piperettine, piperanine, and sarmentine are examples of piperamides. The essential oil of black pepper, which makes up about 1% to 3% of dried berries, is primarily composed of sesquiterpenes (β-caryophyllene, β-bisabolene, δ-elemene, elemol, α-muurolol, and germacrene) and monoterpenes (α-pinene, β-pinene, myrcene, limonene, α-phellandrene, sabinene, terpinolene, and linalool) (Grimont and Weill, 2007; Trindade *et al*., 2021; Bai *et al*., 2023) [12, 20, 52]. Piperine enhances gastrointestinal health, increases food absorption, and supports cognitive brain function. The antioxidant, antibacterial, anti-inflammatory, gastro-protective, and antidepressant properties of black pepper are explained (Mandal *et al*.,2023; Zhao *et al*., 2024) [32, 59]. Ancient maritime trade networks and European exploration of India's southern coast were fueled by this valuable cash, rent, and dowry item. Crushed peppercorn decoctions are used by indigenous rural people as natural anti-parasitic

remedies for livestock and as environmentally friendly botanical biopesticides/larvicides against mosquito vectors and stored-grain weevils.

Cumin (*Cuminum cyminum*)

Zeera, another name for cumin, is the dried seeds of the *Cuminum cyminum* plant, which belongs to the Apiaceae family of parsley. Together, Gujarat and Rajasthan account for more than 90% of India's entire production of cumin (jeera). Organic acids, phenolics, and volatile essential oils are the main phytochemical classes found in cumin (*Cuminum cyminum*). The main class of cumin essential oil is terpenes and terpenoids, which account for at least 45–50% of the volatile portion. γ-terpinene, p-cymene, β-pinene, α-pinene, β-myrcene, and limonene are examples of monoterpenes. Aldehydes, including p-mentha-1,3-dien-7-al, p-mentha-1,4-dien-7-al, and myrtenal, are mostly driven by cuminaldehyde (Patil *et al*., 2003; Sekine *et al*., 2007) [45]. In addition to its digestive and diabetogenic qualities, cumin has antioxidant, anti-inflammatory, insecticidal, anti-inflammatory, analgesic, antioxidant, anticancer, antidiabetic, anti-platelet-aggregation, hypotensive, bronchodilatory, immunological, contraceptive, anti-amyloidogenic, anti-osteoporotic, and antibacterial qualities, indicating that it may be a potential dietary option for controlling and treating a number of chronic conditions (Hajlaoui *et al*., 2010) [22]. These therapeutic qualities result from the different phytochemicals it contains. used as an effective stomachic, antispasmodic, and carminative. Every day, boiled cumin water, also known as Jeera water, is given to treat dyspepsia, diarrhoea, bloating, and gas. Cumin has a major role in postpartum care (VanderJagt *et al*., 2002; Jabbar, 2013) [23, 53]. It is frequently administered to nursing women to tone the uterus and encourage lactation (galactagogue characteristics). An indigenous treatment for chest congestion that relieves chronic coughs and acts as a moderate bronchodilator is a mixture of cumin powder and honey.

Turmeric (*Curcuma longa*)

Turmeric is a member of the Zingiberaceae family of ginger plants and is referred to as "turmeric" in English (Botanical name: *Curcuma longa*) and "Haldi" in Hindi. The Indian states that produce the most turmeric include Maharashtra, Telangana, Tamil Nadu, Karnataka, and Madhya Pradesh. Curcuminoids, volatile oils/terpenes, and other bioactive plant compounds like flavonoids, tannins, and alkaloids are the main families of the more than 300 active phytochemicals found in turmeric. Main Classes of Phytochemicals in Turmeric are curcuminoids like curcumin (diferuloylmethane, bisdemethoxycurcumin, demethoxycurcumin), cyclocurcumin, volatile oils and terpenes include Ar-turmerone, α-turmerone and β-turmerone, zingiberene – A sesquiterpene also common in ginger, germacrone and curcumene (Ahmed *et al*., 2015; Sharifi-Rad *et al*., 2020; Mansouri *et al*., 2020) [34, 46]. The *Curcuma longa* plant yields the golden spice known as turmeric, which is high in curcumin, an active substance. Strong anti-inflammatory, antioxidant, and antibacterial qualities make it well-liked for improving digestion, reducing joint pain, and strengthening immunity in general (Tung, 2019; Fuloria *et al*., 2022) [11, 18]. In India and Indonesia, new mothers and babies are historically rubbed or anointed with turmeric paste for skin health, longevity, and protection from birth until death. A common pre-wedding tradition in South Asia is to anoint the bride and groom with haldi (turmeric paste) to bless them and cleanse their skin. It is a mainstay of everyday devotion, temple rites, and celebrations like Odisha's Raja festival because it is seen as a symbol of purity, prosperity, and warding off harmful spirits.

Coriander (*Coriandrum sativum*)

Coriander is a member of the Apiaceae family, which was once known as the Umbelliferae or the carrot/parsley family. It is also referred to as Dhaniya in Hindi. Madhya Pradesh, Rajasthan, and Gujarat are India's three main coriander-producing states. Together, they produce the great majority of the nation's commercial seed-spice output. Uttar Pradesh, Assam, West Bengal, Andhra Pradesh, Telangana, and Karnataka are other important producing states. Linalool (coriandrol), a monoterpenoid that accounts for between 40% and 87% of the essential oil in the seeds and leaves of coriander (*Coriandrum sativum*), is the primary phytochemical in this plant. Coriander (*Coriandrum sativum*) is rich in diverse phytochemicals, notably monoterpenoids (such as linalool, camphor, and geraniol), phenolic acids (such as caffeic, chlorogenic, and ferulic acids), flavonoids (such as quercetin and kaempferol), and fixed oils rich in petroselinic acid. Essential Oils and Terpenoids include Linalool, α-Pinene, β-Pinene, Camphor, Geraniol, Limonene, γ-Terpinene (Marzouk, 2005) [35]. Phenolic Acids, Polyphenols, Caffeic Acid, Chlorogenic Acid, Ferulic Acid, Gallic Acid, Vanillic, *p*-Coumaric Acids- Quercetin, Flavonoids, Kaempferol, Apigenin, Rutin, Luteolin, Myricetin (Msaada *et al*., 2007; Ashok Kumar *et al*., 2010) [10, 36]. Coriander seeds (*Coriandrum sativum*) have many therapeutic uses, most notably as an antioxidant, blood sugar regulator, and natural digestive aid. The antibacterial, antifungal, antioxidant, anti-inflammatory, and antimicrobial qualities of coriander essential oils make them widely employed in medicine (Begnami *et al*., 2010) [13]. They have active ingredients that promote heart health, lower inflammation, and fight bacteria, such as linalool, quercetin, and essential oils. While dried seeds are a key ingredient in curry powders, fresh leaves (cilantro or hara dhanya) are used as a raw garnish in South Asian, Mexican, and Mediterranean recipes (Khare *et al*., 2004) [27]. Plant components are used by traditional healers to treat mouth ulcers, headaches, joint discomfort, and gastrointestinal problems. The herb is mentioned as dhanyaka in the Torah and ancient Sanskrit scriptures, and preserved seeds have been discovered in Egyptian tombs such as Tutankhamun's.

Clove (*Syzygium aromaticum*)

Clove is referred to as Clove in English and Laung in Hindi. *Syzygium aromaticum* is its botanical name, and it is a member of the Myrtaceae (myrtle family) family of plants. With more than 80% of India's total clove production, Tamil Nadu is the state that produces the most cloves. The major phytochemical classes present in clove (*Syzygium aromaticum*) include phenylpropanoids, terpenes (monoterpenes and sesquiterpenes), flavonoids, and phenolic acids. Phenylpropanoids include Eugenol, Eugenyl acetate (Acetyl eugenol), Methyl salicylate. Terpenes & Terpenoids include β-Caryophyllene, α-Humulene, Caryophyllene oxide, Oleanolic acid (triterpenoid). Flavonoids include Quercetin, Kaempferol, Eugenin,

Rhamnetin and Ellagic acid, Phenolic Acids, Caffeic acid, Ferulic acid, Gallic acid (Srivastava *et al*., 2005; Jirovetz *et al*., 2006; Santamarina *et al*., 2016) [8, 24, 49]. *Syzygium aromaticum* essential oils and extracts showed potent antioxidant qualities (Dudonne *et al*., 2009; Gulcin *et al*., 2012; Ali *et al*, 2016) [8, 16, 21]. Cloves have antibacterial and anti-inflammatory properties because they are high in essential oils, especially eugenol (Kmatou *et al*., 2012) [25]. They also include minerals like fiber and manganese, as well as vitamins like vitamin C. Cloves have been used in traditional medicine to treat respiratory, digestive, and dental disorders in addition to cookery, demonstrating their diverse historical roles in both gastronomy and health. Because eugenol has a local anesthetic effect, biting or applying whole cloves and clove oil directly to gums or cavities is a traditional therapy used all over the world for toothaches, gum inflammation, and oral ulcers. Indigestion, gas, nausea, and stomach spasms are frequently treated with clove teas and infusions. Cloves are steeped in hot water or warm milk with honey in places like South Asia and North Africa to relieve sinus congestion, sore throats, and coughs.

Feniugreek (*Trigonella foenum-graecum*)

Fenugreek, or *Trigonella foenum-graecum*, is a member of the Fabaceae family of plants, which was once known as the Leguminosae. It is referred to as Fenugreek in English and Methi in Hindi. Rajasthan is the state that produces the most fenugreek in India, making up a significant portion of the nation's total (typically between 40% and 80%, depending on the crop year and data source). Bioactive phytochemicals found in fenugreek (*Trigonella foenum-graecum*) include alkaloids (like trigonelline and choline), steroidal saponins (like diosgenin and yamogenin), flavonoids (like apigenin and luteolin), mucilaginous dietary fibers (like galactomannans), and the special free amino acid 4-hydroxyisoleucine (Srinivasan, 2006; Acharya *et al*., 2008; Navarro *et al*., 2021; Singh *et al*., 2023; Prakash *et al*., 2025) [3, 37, 40, 47, 48]. This seed shows encouraging therapeutic promise for treating a variety of medical conditions. Importantly, these results show notable characteristics including antidiabetic, antioxidant, anti-obesity, hypocholesterolemic, anticancer, and cardioprotective actions (Alkofahi *et al*., 1996) [9]. Traditionally, it has been used as a uterine or general restorative tonic and to encourage nursing mothers to produce more breast milk. Ground powders and soaked seeds ("methi water") are used to support healthy blood sugar and cholesterol levels, reduce constipation through mucilage, and soothe digestive fire (Agni) (Raghuram *et al*., 1994) [42]. Lepa, a mucilaginous paste made from crushed, water-soaked seeds, is traditionally applied to the scalp and hair for conditioning or used in poultices for localized irritation.

Cinnamon (*Cinnamomum verum*)

Dalchini, also known as True/Ceylon Cinnamon in English, is a Hindi term for cinnamon. It belongs to the family Lauraceae and is botanically known as *Cinnamomum verum* (synonym: *Cinnamomum zeylanicum*). Kerala is the biggest producer of cinnamon in India, followed by Tamil Nadu and Karnataka. Cinnamon is mostly grown in the southern states around the Western Ghats. The first northern state to start organizing the production of genuine cinnamon was Himachal Pradesh. Volatile essential oils and non-volatile polyphenols make up the rich array of bioactive phytochemicals found in cinnamon. About 60% to 90% of cinnamon bark essential oil is made up of cinnamaldehyde (trans-cinnamaldehyde), the main volatile component that gives it its distinctive flavour, smell, and potent antibacterial and antioxidant properties (Yap *et al*., 2015; Ainane *et al*., 2019; Garg and Kumar, 2019) [7, 19, 56]. Compounds such as β-caryophyllene, linalool, alpha-cubebene, cadinene, procyanidins and catechins, coumarin, terpenoids, and sesquiterpenes (Ahmed *et al*., 2020) [5]. Cinnamaldehyde and polyphenols are two of the key plant chemicals that give cinnamon its many traditional and scientifically validated therapeutic benefits. Cinnamon has been shown to have effects against neurological conditions including Parkinson's and Alzheimer's illnesses in addition to being an anti-inflammatory, antioxidant, antidiabetic, antibacterial, anticancer, lipid-lowering, and cardiovascular disease-lowering substance (Zarai *et al*., 2013; Mallick *et al*., 2016) [30, 57]. It is a fundamental component in garam masala. At the beginning of meals, it is methodically fried in heated oil to release lipid-soluble components that improve digestion and stop food from spoiling. It's interesting to note that Tejpatra, or Indian bay leaf, is made from the leaves of some comparable Cinnamomum species that are produced in India. This serves as an additional layer of ethnobotanical practice in the home.

Green Cardamom (*Elettaria cardamomum*)

The perennial spice plant known as green cardamom (*Elettaria cardamomum*) is a member of the Zingiberaceae family, which includes ginger. It is referred to as "green cardamom" or "true cardamom" in English, and Chhoti Elaichi, or simply Elaichi, in Hindi. Kerala, Karnataka, and Tamil Nadu are the three main Indian states that produce green cardamom (choti elaichi). Kerala is the leading producer, accounting for between 70 and 90 percent of the nation's total production, which is mostly centered in the Western Ghats and Idukki district. More than 90% of the essential oil of cardamom is composed of monoterpenes and oxygenated monoterpenes. The most well-known substances include 1,8-cineole/eucalyptol, α-terpinyl acetate, linalool and linalyl acetate, limonene, and sabinene. Myrcene and α-terpineol (Satyal., *et al*., 2012; Abdullah *et al*, 2021) [1, 44]. It has a number of pharmacological characteristics, including anti-inflammatory, antibacterial, antioxidant, and anticancer effects (DeLeo *et al*., 2009; Abdullah, 2017; Yahyazadeh *et al*., 2021 [2, 26, 55]; Ramdan *et al*., 2022). included into everyday spiced teas, holiday rice meals (biryani), traditional sweets (kheer, payasam), and temple offerings. a key component of several regional Indian spice recipes, including Garam Masala. Due to its oil content and export quality, well-known local products like Alleppey Green Cardamom have protected Geographical Indication (GI) status.

Thyme (*Trachyspermum ammi*)

Trachyspermum ammi a member of the Apiaceae family, is the scientific name for ajwain. In the past, it was also referred to by the botanical synonyms *Ammi copticum* and *Carum copticum*. Thyme is mostly grown on a limited scale in mountainous, temperate parts of India and is not a significant mainstream crop. Uttarakhand, Himachal Pradesh, Jammu & Kashmir, and Tamil Nadu (particularly the Nilgiris) are the main Indian states that produce thyme. Thyme (Thymus vulgaris and allied species) has a rich

matrix of volatile and non-volatile secondary metabolites, essential oils, phenolic acids, flavonoids, and minerals, according to a phytochemical investigation. In French and German winter chemotypes, thymol ranges from 10% to 64%, or roughly 37% to 55%. Carvacrol, p-Cymene, γ-Terpinene, linalool (β-linalool), and borneol are other phytochemicals (Tabssi *et al*., 2016; Kowalczyk *et al*., 2020; Fathimathul *et al*., 2025) [17, 28]. This is explained by its numerous pharmacological characteristics, which include anti-inflammatory, analgesic, antiviral, insecticidal, antimicrobial, antiaging, antioxidant, and antineoplastic effects, among others (Rajeshwari *et al*., 2011) [41]. Furthermore, thyme has long been recognized for its amazing breakdown of microbial biofilms as well as its antiviral, antibacterial, antifungal, and antiseptic properties. Menstrual cramps, flatulence, nausea, diarrhea, indigestion, and low appetite can all be relieved by their carminative qualities (Zarshenas *et al*., 2013) [58]. Thymus linearis juice, decoction, or herbal infusion is commonly used in Himalayan folk traditions to treat bronchitis, whooping cough, coughs, colds, flu, and chest congestion. It is also useful for relieving congestion in the ears and sinuses. Teas and plant decoctions are used as preventative or curative treatments for gas, indigestion, and stomach discomfort. Children have historically been given plant concoctions to aid in the removal of intestinal worms (such as roundworms and threadworms) (Waheed *et al*., 2024) [54]. Thyme is known for its bitter (Tikta) and astringent (Kashaya) flavors, which support digestion (Agni), calm Kapha, and open respiratory channels.

Fennel (*Foeniculum vulgare*)

Fennel (*Foeniculum vulgare*) is a member of the Apiaceae (or Umbelliferae) family and is referred to as Saunf in Hindi. With more than 70% to 90% of India's total production, Gujarat is the state that produces the most fennel (saunf). Flavonoids, phenolic chemicals, volatile essential oils, and dietary elements are all abundant in fennel seeds. Phenylpropanoids and monoterpenes, such as trans-anethole, fenchone, D-limonene, α-pinene, α-phellandrene, and estragole, predominate in essential oils (Afify *et al*., 2011) [4]. Rosmarinic acid, chlorogenic acid, variants of caffeoylquinic acid, and miquelianin are examples of phenolic acids. Dillapional, a phenylpropanoid derivative derived from the stem of F. vulgare, and scopoletin, a coumarin derivative, were discovered to have a slight antibacterial effect (Kwon *et al*., 2002) [29]. When compared to the reference fungicidal agent, griseofulvin, F. vulgare had the strongest antifungal efficacy (Taie *et al*., 2013) [51]. In traditional medicine, fennel seeds (Foeniculum vulgare, also known as saunf) are frequently used to improve breath, ease menstrual cramps, lessen bloating, and aid digestion. It has antibacterial, antifungal, antiviral, diuretic, anti-inflammatory, analgesic, antioxidant and antispasmodic activities (Kaur and Arora, 2009; Manonmani and Khadir, 2011; Orhan *et al*., 2012; Dua *et al*., 2013) [15, 26, 33, 38]. Packed with active ingredients like fiber and anethole, they also aid in blood sugar regulation and support lactation in nursing moms. Additionally, fennel can be used as a lead ingredient for bioactive compounds that may have additional advantageous pharmacological activities thanks to phytosterols, lignans, and polyacetylenes. (Manal *et al*., 2025) [31]. In Indian homes and restaurants, they are commonly chewed raw, roasted, or sugar-coated (sauf/mukhwas) after meals to boost digestive juices and improve breath. Known as Madhurika, it has a sweet flavor (madhura), a hint of heat (ushna), and a special ability to calm the three doshas (Kapha, Pitta, and Vata).

Conclusion

Indian spices are a perfect example of how contemporary biomedical research and traditional Ayurvedic knowledge may coexist harmoniously. Bioactive substances including piperine, curcumin, eugenol, cinnamaldehyde, and thymol not only improve flavor but also function as potent anti-inflammatory, antioxidant, antidiabetic, and digestive agents that help control the body's doshas and guard against long-term diseases.

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