A Review on Curcumin and Its Role in the Food Industry

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ABSTRACT;

Curcumin, the principal curcuminoid found in Curcuma longa (turmeric), has attracted significant attention in the food industry due to its potent antioxidant, anti-inflammatory, antimicrobial, and coloring properties. Extracted primarily from turmeric rhizomes, curcumin is used not only as a natural food additive and preservative but also as a functional and therapeutic component in nutraceuticals and intelligent packaging systems. Despite its broad applications, curcumin's poor water solubility, low bioavailability, and chemical instability pose critical challenges in its effective use. To overcome these limitations, advanced extraction and delivery techniques such as solvent extraction, column chromatography, nanoencapsulation, and lipid-based carriers have been developed to enhance curcumin's stability, solubility, and functional performance. Furthermore, curcumin-infused films and edible coatings are being applied in active packaging to extend food shelf life and monitor freshness. This review highlights the natural sources of curcumin, its extraction techniques, multifunctional properties, wide-ranging food applications, and the strategies being explored to address its technological limitations, thereby establishing curcumin as a valuable, multifunctional compound in the modern food industry.

Key Words; *Curcumin, Turmeric (curcumin longa), Antioxidant, Active food packaging*

1. Introduction;

Turmeric is a product of Curcuma longa, a rhizomatous herbaceous perennial plant belonging to the ginger family Zingiberaceae, which is native to tropical South Asia. As many as 133 species of Curcuma have been identified worldwide (Srinivasan et al. 2011). Most of them have common local names and are used for various medicinal formulations. The turmeric plant needs temperatures between 20°C and 30°C and a considerable amount of annual rainfall to thrive. Individual plants grow to a height of 1 m, and have long, oblong leaves. Plants are gathered annually for their rhizomes and are reseeded from some of those rhizomes in the following season. The rhizome, from which the turmeric is derived, is tuberous, with a rough and segmented skin (Rahman et al. 2022). The rhizomes mature beneath the foliage in the ground. They are yellowish brown with a dull orange interior. The main rhizome is pointed or tapered at the distal end and measures 2.5–7.0 cm (1–3 inches) in length and 2.5 cm (1 inch) in diameter, with smaller tubers branching off. When the turmeric rhizome is dried, it can be ground to a yellow powder with a bitter, slightly acrid, yet sweet, taste. Among the various sources, turmeric is by far the most abundant and commercially significant source of curcumin. Other related plant species within the *Curcuma* genus contain curcuminoids in smaller amounts, but are not widely used for curcumin extraction. Due to its health-promoting properties, curcumin is extensively used in the food, pharmaceutical, and cosmetic industries. Understanding the natural sources of curcumin is essential for its efficient extraction, application, and research (Hewlings et al. 2017).

2. Source of the curcumin

The primary and most significant source of curcumin is turmeric (*Curcuma longa* L.), a perennial herb widely cultivated in tropical regions (Ammon et al. 1991). The rhizomes of *Curcuma longa* contain approximately 2–5% curcuminoids, with curcumin accounting for about 77% of the total curcuminoid content. The other major curcuminoids include demethoxycurcumin and bisdemethoxycurcumin. Curcumin is typically extracted from dried turmeric powder using solvents such as ethanol, methanol, acetone, or through supercritical CO_2 extraction for higher purity and efficiency (Liu et al., 2016). India plays a dominant role in turmeric production, contributing to over 75% of global output, making it the leading producer and consumer. In addition to *Curcuma longa*, other species such as *Curcuma aromatica* (commonly known as wild turmeric) and *Curcuma zedoaria* (white turmeric) also contain curcuminoids (Chattopadhyay et al., 2004). However, their curcumin content is significantly lower, making them less favorable for large-scale extraction. These species are traditionally used in herbal medicine and cosmetic formulations, rather than for curcumin extraction (Gupta et al., 2013).

2.1. Turmeric (Curcuma longa L.) – Primary Source

- Rhizomes contain 2–5% curcuminoids, of which curcumin is the major constituent (~77% of the total curcuminoids), followed by demethoxycurcumin and bisdemethoxycurcumin.
- **Form**: Curcumin is mainly extracted from dried turmeric powder using solvents like ethanol, methanol, acetone, or supercritical CO_2.
- **Cultivation**: India is the largest producer and consumer of turmeric, contributing over 75% of global production.(Shreiner et al., 2015)

2.2. Other Curcuma Species (Secondary Sources)

- Curcuma aromatica (Wild turmeric) and Curcuma zedoaria (White turmeric) also contain curcuminoids, but in much lower concentrations compared to Curcuma longa.
- These are used traditionally in herbal medicine and cosmetics, but are not preferred for curcumin extraction due to lower yields (Shreiner et al., 2015).

2.3. Curcumin Extracts and Supplements

- Commercial supplements or standardized curcumin extracts (like Curcumin C3 Complex®, Meriva®, BCM-95®) are derived from turmeric but are highly purified and often combined with absorption enhancers like piperine (from black pepper) or phospholipids.

- These products are widely used in nutraceutical and pharmaceutical industries for their anti-inflammatory, antioxidant, and anticancer properties (Hewlings et al. 2017).

Table 1; Sources of Curcumin

Source	Scientific Name	Curcumin Content	Observation
Turmeric root	*Curcuma longa*	~2–5%	Main and richest source
Wild turmeric	*Curcuma aromatica*	Low	Used in cosmetics, not dietary
White turmeric	*Curcuma zedoaria*	Very low	Contains different active compounds
Black turmeric	*Curcuma caesia*	Minimal	Rare, used in traditional medicine

(Source; Prasad et al. 2014)

3. Various extraction techniques of Curcumin

Extraction and separation of curcumin from turmeric powder was reported way back in 1815, more improved and advanced extraction methods are still being reported, even after two centuries. Solvent extraction followed by column chromatography has been the most commonly employed method reported for separating curcumin from turmeric.

3.1 Solvent extraction method

Solvent extraction in curcumin extraction is a method used to separate curcumin from turmeric using a suitable solvent (such as ethanol, methanol, or acetone) that dissolves curcumin, allowing it to be extracted from the turmeric powder.

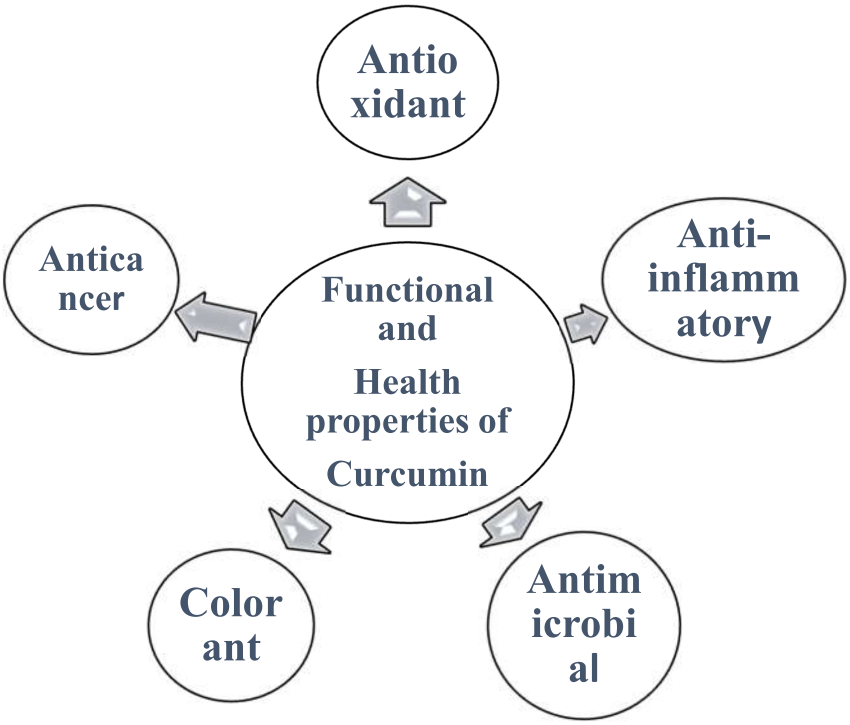
Solvents used are of AR/HPLC grade and obtained from E-Merck or ethanol, methanol, acetone.

Process: The extraction requires the turmeric roots to be ground into powder by using mortar. After that it is air dried to remove the moisture present in the feed or ground powder, and then a known amount of turmeric powder say 10 grams is weighed accurately and then it is washed or treated with suitable solvent like acetone, ethanol etc., in the extraction column to extract the solute or curcumin present in the turmeric powder for a desired time. And then distillation is performed to separate the mixture of solvent and solute. It is performed just by heating the mixture up to the boiling point of either solvent or solute here we heat up to the boiling point of solvent because it is having low boiling point when compared to solute. The oleoresin so obtained is subjected to further washes using selective solvents. Here we use hexane as a solvent because it has high absorption coefficient. After washing has performed it leave out a powdered, purified food colour know as curcumin powder (Shreiner et al., 2015).

3.2 column chromatography;

Curcumin is an important food additive and a potential therapeutic agent for various diseases from turmeric, the rhizome of Curcuma longa L. High-efficient column chromatographic extraction (CCE) procedures were developed for the extraction of curcumin from turmeric. Turmeric powder was loaded into a column with 2-fold 80% ethanol. The column was eluted with 80% ethanol at room temperature. For quantitative analysis with a non-cyclic CCE, 8-fold eluent was collected as extraction solution. For large preparation with a cyclic CCE, only the first 2-fold of eluent was collected as extraction and other eluent was sequentially circulated to the next columns. More than 99% extraction rates were obtained through both CCE procedures, compared to a 59% extraction rate by the ultrasonic-assisted maceration extraction with 10-fold 80% ethanol. The CCE procedures are high-efficient for the extraction of curcumin from turmeric with minimum use of solvent and high concentration of extraction solution (Zhan et al., 2011).

4. Functional and health Properties



A. Antioxidant

Curcumin, the principal bioactive compound in turmeric (*Curcuma longa*), exhibits potent antioxidant properties primarily due to its unique chemical structure, which includes phenolic and methoxy groups as well as a diketone moiety. These structural features enable curcumin to scavenge reactive oxygen species (ROS) such as superoxide anions, hydroxyl radicals, and nitric oxide, thereby protecting cells from oxidative damage. Additionally, curcumin can enhance the activity of endogenous antioxidant enzymes, including superoxide dismutase (SOD), catalase, and glutathione peroxidase. It also plays a role in inhibiting lipid peroxidation by disrupting free radical chain reactions in membrane lipids. Beyond direct scavenging, curcumin can modulate signaling pathways such as Nrf2 (nuclear factor erythroid 2–related factor 2), which regulates the expression of genes involved in the antioxidant response. These multiple mechanisms contribute to curcumin's protective effects against oxidative stress, which is linked to aging and various chronic diseases such as cancer, cardiovascular disorders, and neurodegenerative conditions (Aggarwal et al., 2007).

B. Anti-inflammatory

Curcumin, the principal curcuminoid found in turmeric (*Curcuma longa*), exhibits potent anti-inflammatory activity through multiple molecular mechanisms. It acts primarily by inhibiting key signaling pathways that regulate inflammation. One of its main targets is the nuclear factor-kappa B (NF-κB) pathway, which controls the expression of various pro-inflammatory cytokines such as tumor necrosis factor-alpha (TNF-α), interleukin-6 (IL-6), and interleukin-1β (IL-1β). Curcumin suppresses the activation of NF-κB by inhibiting IκB kinase (IKK), thereby preventing the translocation of NF-κB to the nucleus (Aggarwal & Harikumar, 2009). Additionally, curcumin downregulates the activity of cyclooxygenase-2 (COX-2) and lipoxygenase (LOX), enzymes responsible for the synthesis of inflammatory mediators like prostaglandins and leukotrienes (Jurenka, 2009). Curcumin also exerts antioxidant effects by neutralizing free radicals and enhancing the activity of endogenous antioxidant enzymes, which indirectly contributes to its anti-inflammatory action. Due to these mechanisms, curcumin has been explored for therapeutic use in conditions such as arthritis, inflammatory bowel disease, and cardiovascular disorders.

C. Antimicrobial

Curcumin, the principal bioactive compound of turmeric (*Curcuma longa*), exhibits significant antimicrobial activity against a wide range of microorganisms, including bacteria, fungi, and viruses. Its antimicrobial action is primarily attributed to its ability to disrupt the integrity of microbial cell membranes, interfere with nucleic acid synthesis, and inhibit essential enzymes involved in microbial metabolism. Curcumin has been shown to exert bacteriostatic or bactericidal effects against both Gram-positive and Gram-negative bacteria such as *Staphylococcus aureus*, *Escherichia coli*, *Pseudomonas aeruginosa*, and *Bacillus subtilis*. It induces oxidative stress in microbial cells by generating reactive oxygen species (ROS), leading to cell damage and apoptosis. Additionally, curcumin inhibits quorum sensing in bacteria, thereby reducing virulence and biofilm formation, which are major contributors to antimicrobial resistance. Its antifungal effects have also been documented, particularly against *Candida* species, where it disrupts membrane function and reduces ergosterol content. Furthermore, curcumin's antiviral potential has been observed in studies against HIV, influenza, and hepatitis viruses, primarily through inhibition of viral replication and modulation of host immune responses. The synergistic effect of curcumin when combined with conventional antibiotics has also been reported, enhancing antimicrobial efficacy and potentially reversing antibiotic resistance (Tyagi et al., 2015).

D. Colorant

Curcumin, the principal curcuminoid found in turmeric (*Curcuma longa*), acts as a natural colorant due to its bright yellow to orange hue. This pigmentation arises from its conjugated double bond system and diketone structure, which strongly absorb visible light, particularly in the 420–430 nm range, imparting an intense yellow color to foods and other products. Curcumin is widely used in the food industry as a coloring agent under the code E100. Its stability and solubility vary depending on pH, light, and temperature conditions—it is more stable in acidic environments, making it suitable for coloring beverages, dairy, and bakery products. In addition to its coloring properties, curcumin is favored over synthetic dyes due to its natural origin and added health benefits, such as antioxidant and anti-inflammatory properties. However, its poor water solubility and sensitivity to light may limit its application in some formulations, which is often addressed by using encapsulation techniques or emulsification (Paramasivam et al., 2009).

E. Anticancer

Curcumin, the primary bioactive compound in turmeric (*Curcuma longa*), has been extensively studied for its anticancer properties due to its ability to modulate multiple cellular signaling pathways. It exhibits anticancer activity by inducing apoptosis (programmed cell death) in cancer cells, inhibiting cell proliferation, and suppressing tumor growth and metastasis. One of the key mechanisms involves the downregulation of nuclear factor-kappa B (NF-κB), a transcription factor that controls genes responsible for inflammation, cell survival, and proliferation. Curcumin also inhibits angiogenesis (formation of new blood vessels in tumors), thereby limiting the nutrient supply to cancer cells. Moreover, it affects the expression of various oncogenes and tumor suppressor genes such as p53, Bcl-2, Bax, and caspases, enhancing apoptotic pathways while reducing cell survival mechanisms. Its antioxidant and anti-inflammatory properties further contribute to its chemopreventive effects. Due to its ability to target multiple molecular targets with minimal toxicity, curcumin is considered a promising natural compound for cancer therapy, especially as an adjuvant to conventional chemotherapy or radiotherapy (Anand et al., 2008).

5. Application in food industry

Curcumin, a polyphenolic compound derived from turmeric, has emerged as a valuable ingredient in the food industry due to its vibrant yellow color and health-promoting properties. It is commonly used as a natural additive to replace synthetic food dyes and also functions as an antioxidant and antimicrobial agent, helping to delay spoilage and extend product shelf life. Curcumin's presence enhances the functional value of food items, especially in the formulation of nutraceuticals, health drinks, and dairy products. It has also shown promise in active food packaging to prevent microbial growth. Despite its beneficial roles, curcumin’s application is limited by its poor water solubility and bioavailability. To overcome these challenges, researchers have developed innovative methods such as encapsulation in biopolymers, emulsions, and nanoparticles, which allow for improved integration into diverse food systems (Ahmed et al., 2020).

A. Natural food colorant

Curcumin (E100), the vibrant yellow-orange pigment extracted from turmeric (*Curcuma longa*), has become an increasingly popular natural food colorant, effectively replacing synthetic dyes like tartrazine and enhancing both the aesthetic and nutritional appeal of food products. Its intense color is leveraged across a wide array of applications—from bakery and confectionery items such as cakes, cookies, and icings, to dairy products like yogurt, cheese, and ice cream, as well as beverages and snack foods (Sharifi-Rad et al., 2020).

Its compatibility with both hot and cold processing systems, along with regulatory approvals by bodies such as the FDA and EFSA, have facilitated its widespread use in clean-label and functional food products. To address curcumin's sensitivity to light, pH, and poor solubility, modern formulation technologies like nanoencapsulation, emulsions, and cyclodextrin complexes have been developed to improve its stability and enable homogeneous coloring in aqueous matrices like yogurt. curcumin exemplifies a multifunctional ingredient that adds both visual flair and functional benefits, aligning with current consumer trends toward natural, health-promoting food additives (Gandhi et al., 2018).

B. Preservative effect

Curcumin's preservative effects in the food industry stem largely from its potent antimicrobial, antioxidant, and acid-regulating properties, which can significantly extend shelf life and enhance food safety. Incorporating turmeric extract at approximately 0.6–5% into paneer cheese has been shown to extend refrigerated shelf life by up to 12 days by inhibiting spoilage microbes. The antimicrobial efficacy of curcumin microcrystals has also been demonstrated in minimally processed carrots, effectively suppressing *Bacillus cereus, Staphylococcus aureus, E. coli,* and *Pseudomonas aeruginosa* without altering sensory quality (Buch et al. 2015). Advancements in encapsulation and nanoemulsion technologies enable curcumin to disperse better in aqueous food systems and enhance its preservative action. In cheese and butter, nanoemulsion-based curcumin not only improved physicochemical stability during storage but also inhibited pathogens like *S. aureus* and *E. coli.* In yogurt, encapsulated curcumin exhibited synergistic antimicrobial effects with probiotic bacteria, suppressing coliforms, yeasts, and fungi over 28 days. edible coatings and packaging infused with curcumin (e.g., chitosan/γ-polyglutamic acid films for beef, and β-cyclodextrin-or alginate-based cheese coatings) significantly extended shelf life, preserved meat quality, and provided antimicrobial protection (Bagale et al. 2023).

C. Functional/ Health foods

Curcumin has been extensively integrated into functional and health-focused foods due to its potent antioxidant, anti-inflammatory, and antimicrobial properties. Studies demonstrate that curcumin-enriched foods such as breads, yogurts, smoothies, and meat products can significantly enhance antioxidant capacity, stabilize lipids, and prolong shelf life without altering sensory attributes. Incorporating curcumin into chicken nuggets elevated vitamin E concentration and antioxidant activity, while turmeric extract helped prevent lipid oxidation in lamb sausages (Priyadarsini, 2014). Advanced formulations like nanoemulsions, liposomes, and biopolymer-based delivery systems (e.g., β-cyclodextrin, mesoporous silica, chitosan films) have been developed to improve curcumin's stability, bioavailability, and controlled release, enabling its effective inclusion in functional beverages, dairy, and meat products . Additionally, curcumin-incorporated active and intelligent packaging—including pH-sensitive films and edible coatings—provides dual benefits: enhancing food safety via antimicrobial activity and offering freshness monitoring via visual color shifts. these innovations position curcumin not just as a colorant, but as a multifunctional nutraceutical ingredient that meets consumer demand for health-promoting, clean-label products in the modern food industry (Hosseini et al., 2013).

D. Packaging films

Curcumin has emerged as a promising natural agent for active and intelligent food packaging films, where it serves dual functions as both an antimicrobial/antioxidant compound and a pH-sensitive freshness indicator. For instance, gelatin–chitosan films embedded with curcumin act as photosensitizers that, when activated by blue light (455 nm), generate reactive oxygen species (ROS) capable of reducing *Listeria monocytogenes*, *E. coli*, and *Shewanella* by over 4.5 log CFU/mL (>99.99 %)—demonstrating powerful antimicrobial activity for non-thermal food sterilization (Lu *et al.* 2022). Chitosan/polyvinyl alcohol films incorporating curcumin complexes show excellent radical scavenging (ABTS 98 %, DPPH 87 %), inhibit both *S. aureus* and *E. coli* by up to ~2.7 log CFU/mL, and display visible color changes in response to shrimp spoilage—enabling real-time freshness monitoring. Other biopolymer matrices, such as pectin–gelatin films with curcumin and silver nanoparticles, demonstrate robust antimicrobial action and pH-responsive discoloration shifting from yellow to red as food deteriorates. Additionally, curcumin in gelatin films enhances UV-blocking, strengthens water vapor barriers, and provides significant antioxidant activity—comparable to ascorbic acid—while inhibiting foodborne pathogens (Zhang *et al.* 2024).

6. Challenges and Limitations

- Curcumin's promising role in the food industry is hindered by several notable challenges. Primarily, its **poor water solubility and low bioavailability** restrict its effective incorporation into aqueous-based food products and nutritional systems.

- As a hydrophobic compound with a high melting point, curcumin exhibits minimal solubility in gastrointestinal fluids, limiting its absorption and health efficacy. It is **chemically unstable**, undergoing pH-dependent degradation, autoxidation, and photodegradation during food processing and storage. These reactions not only diminish its functional properties but also reduce its visual appeal and antioxidant activity. High temperatures, light, and oxygen exposure further exacerbate its instability in various food matrices.

- These limitations, researchers have developed a range of **micro- and nano-encapsulation delivery systems**—including nanoemulsions, liposomes, solid lipid nanoparticles, micelles, and biopolymer-based capsules—that enhance curcumin's solubility, chemical stability, and bioaccessibility. For instance, lipid-based carriers improved simulated gastrointestinal bioaccessibility from ~10% for free curcumin to 40–79%, depending on carrier oil and particle type . Coingestion with **bioenhancers** like piperine or antioxidant agents (e.g., ascorbate) has also shown to significantly inhibit metabolic degradation and enhance plasma retention up to sixfold.

- In the context of **food applications**, these advanced delivery methods enable curcumin to serve reliably as a **natural colorant, antioxidant additive, preservative, and functional ingredient** in products ranging from beverages to smart packaging systems. Encapsulation not only protects curcumin during processing and shelf life but also allows it to be incorporated into **active packaging films** that monitor freshness or inhibit microbial growth using curcumin's photosensitizer abilities.

7. Conclusion

Curcumin stands out as a multifunctional compound in the food industry, owing to its ability to act as a natural colorant, antioxidant, antimicrobial, and health-promoting agent. Sourced predominantly from *Curcuma longa*, curcumin's significance extends beyond flavor and color enhancement, contributing to food preservation, safety, and the development of functional foods. However, its application is limited by inherent challenges such as poor aqueous solubility, low bioavailability, and susceptibility to environmental degradation. Recent advancements in extraction techniques and encapsulation technologies have demonstrated promising results in improving its functional performance and stability in diverse food matrices. Furthermore, its incorporation into intelligent packaging systems reflects curcumin's potential in sustainable and smart food technologies. To fully leverage curcumin's benefits, continued research is essential to optimize delivery systems, ensure regulatory compliance, and maintain sensory quality. Overall, curcumin holds immense promise as a natural, health-enhancing ingredient that aligns with the growing consumer demand for clean-label and functional food products.

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