

Curcumin in Temulawak: Bioavailability, Health Benefits, and Potential Application

Ellyn Patricia¹, Janice Clarisa Tissadharma¹, Kimberly Alecia Theo¹, Natasya Nobelta¹, Livia Janica^{1*}

¹Department of Food Science and Nutrition, i3L University, Jl. Pulomas Barat, Kayu Putih, Jakarta Timur, DKI Jakarta, 13210, Indonesia

*Corresponding author: livia.janica@i3l.ac.id

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HIGHLIGHTS

- ❖ Temulawak contains ~2.3% curcumin with anti-cancer, antimicrobial, and cognitive benefits.
- ❖ Curcumin reduces inflammation by modulating NF-KB and key cytokines
- ❖ Generally safe for human consumption at doses up to 8 g/day, though excessive intake may cause minor gastrointestinal discomfort
- ❖ Micro- and nanoencapsulation utilization is essential to overcome curcumin's natural stability and solubility issues for industrial use

ABSTRACT

Temulawak (*Curcuma xanthorrhiza*), a plant native to Indonesia, has long been utilized in traditional medicine and culinary applications for its rich bioactive profile. Curcumin, the primary bioactive compound, is well-known for its antioxidant, anti-inflammatory, and antimicrobial properties. This review aims to explore the challenges, benefits, and potential applications of curcumin in functional foods and pharmaceuticals. Although curcumin is known for its therapeutic properties in modulating inflammatory diseases, metabolic disorders, and cancer, its low water solubility and rapid metabolism limit its bioavailability. Current research has shown various strategies to enhance curcumin's stability and absorption, including nanoemulsions, biopolymer encapsulation, and phytosome technology. However, despite its broad applications, optimization of curcumin's industrial use remains a challenge. As advancements continue, curcumin's role in product development and innovative applications across various industries should be further researched, with a focus on improving its solubility, controlled delivery systems, and compliance with food and pharmaceutical regulations.



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INTRODUCTION

Background

Temulawak (*Curcuma xanthorrhiza*), commonly known as Javanese ginger, is a native plant found in Indonesia and is typically used as a cooking spice and an ingredient in traditional medicine. Temulawak belongs to the ginger family (*Zingiberaceae*) and is known for its rich bioactive profile, particularly its high curcuminoid content. Curcuminoids are polyphenols studied for their diverse cellular-level biological activities. In Indonesia, temulawak is a key ingredient in *jamu*, a traditional herbal remedy consumed for its benefits in aiding digestive health, protecting liver function, and enhancing immunity (Surya et al., 2024). Its therapeutic effects are mainly attributed to curcumin and its derivatives, known as curcuminoids (dihydrocurcumin, tetrahydrocurcumin, bis-demethoxycurcumin, and demethoxycurcumin). These compounds have been extensively studied for potential health benefits, including their strong antioxidant, anticancer, antibacterial, antimutagenic, and anti-inflammatory properties (Hewlings & Kalman, 2017).

Beyond their traditional use, preclinical and clinical tests suggest that curcuminoids play an important role in reducing oxidative stress, modulating immune responses, and supporting overall cellular homeostasis. This makes them essential in the management of various conditions, including inflammatory diseases, metabolic syndromes, circulatory disorders, diabetes, and bacterial and fungal infections (Alam et al., 2024). At the molecular level, these benefits likely stem from curcumin's ability to modulate inflammatory pathways. Specifically, it suppresses nuclear factor kappa B (NF- κ B), a transcription factor responsible for the expression of pro-inflammatory cytokines such as TNF- α , IL-17, and IL-22 (Cozmin et al., 2024). Through the inhibition of this inflammatory regulator, temulawak-derived curcuminoids are able to provide health-promoting effects. In addition to its medicinal applications, temulawak is also used as a natural yellow pigment, preservative, and pH indicator due to its recognized safety status. According to the U.S. Food and Drug Administration (FDA), curcuminoids are classified as generally safe (GRAS) for consumption (Bertoncini-Silva et al., 2024). This classification is based on extensive scientific evidence demonstrating their safety in food products, providing a clear indication of their safety for human consumption, making it readily available for use in various applications. Furthermore, studies indicate that curcuminoids exhibit low to no toxicity, with no significant adverse effects reported at typical consumption levels, further supporting their use in food and industrial applications (Zheng & McClements, 2020).

However, despite its reported benefits, a major limitation to the practical use of curcumin in functional foods is its poor bioavailability and metabolic instability. This compound has poor solubility and undergoes rapid metabolism, which limits its absorption in the gastrointestinal (GI) tract (Pan-On & Tiyaaboonchai, 2023). To overcome these limitations, researchers have developed various formulations, strategies, and delivery systems to improve curcumin stability, absorption, and bioavailability in food. Methods such as encapsulation using nanoemulsions and biopolymer-based carriers have been shown to be suitable and efficient (Jiang et al., 2020). Microencapsulation enhances the stability and bioavailability of bioactive compounds, such as polyphenols, by shielding them from environmental stressors like oxidation, enzymatic degradation, and unfavorable pH conditions (Bińkowska et al., 2024).

This paper aims to provide a comprehensive review of current advancements in curcumin research, focusing on its bioactive compounds, applications in functional foods, health benefits, and future outlook.

Traditional values

In Asian countries, curcumin is a vital ingredient used in traditional medicine, particularly in Indonesia, Thailand, and India. It is a well-known herbal remedy valued for its anti-inflammatory, antioxidant, antimicrobial, and digestive properties. Herbal medicines are commonly used to regulate the

immune system and restore health. In Indonesia, curcumin is a basic component of *jamu*, Indonesia's traditional herbal drink made of temulawak (turmeric) and tamarind. *Jamu* is traditionally consumed to boost immunity, relieve pain and inflammation, and treat chronic illnesses (Lim & Pranata, 2020). However, limited evidence confirms the benefits and risks of *jamu's* main ingredients.

Similarly, in Thailand, curcumin is frequently used in herbal remedies for digestive issues, such as bloating and indigestion. It is often incorporated into traditional medicinal products, in the form of herbal teas and capsules, believed to promote gut health. Likewise, in India, curcumin plays a significant role in Ayurvedic medicine, where it is traditionally used to treat various illnesses ranging from inflammation to digestive disorders and skin conditions. While traditional herbal medicine has been used for centuries, its benefits and effectiveness are mostly based on experience. Therefore, more scientific research is needed to confirm its effectiveness. While curcumin remains a key component of traditional remedies, modern research has expanded its applications to functional foods, pharmaceuticals, and nutraceuticals, highlighting its versatility beyond traditional medicine.

Utilization

In the food industry, curcumin is commonly used as a natural coloring agent (E100) in processed foods, beverages, and confectionery products due to its vibrant color and stability under certain processing conditions. Additionally, curcumin's antioxidant and antimicrobial properties make it a valuable compound that can help increase a product's shelf life by preventing oxidative degradation and microbial spoilage. Furthermore, beyond food, curcumin is also widely utilized in the pharmaceutical, cosmetic, and textile industries. In the cosmetics industry, it is a common ingredient found in creams, lotions, and serums designed for anti-inflammatory, anti-aging, anti-acne, and wound-healing skincare (Pondini et al., 2023).

Moreover, the textile industry has reported advances in bio-based antimicrobial treatments that use plant-derived compounds. This innovation aims to incorporate green processing methods, reducing reliance on harsh chemicals while enhancing fabric durability (Hossain et al., 2024). Furthermore, curcumin's potential applications are expanding into various fields, including biodegradable packaging and agricultural practices. In biodegradable packaging, curcumin is being incorporated into active food packaging materials to extend shelf life and monitor the quality of food products such as meat and beverages (De Oliveira Filho et al., 2021). Due to their natural antioxidant and antimicrobial properties, curcumin-based films and coatings are being researched as potential biodegradable, non-toxic alternatives to traditional petroleum-based packaging. In agriculture, curcumin-based formulations with antifungal and antibacterial properties are being explored as natural biopesticides and growth enhancers to improve crop production efficiency. These bioactive compounds can offer a sustainable alternative to synthetic pesticides by reducing pesticide dependence and controlling pests through biofilm inhibition (Anas et al., 2024).

SCIENTIFIC APPROACH

Bioactive compounds

Curcumin is a primary bioactive phenolic compound present in temulawak, a plant native to Indonesia. Curcumin is a yellow-orange compound with a molecular weight of 368 g/mol and a melting point of 183°C. It has a linear diarylheptanoid structure composed of two aromatic benzene rings connected to one hydroxy and methoxy substituent. It is linked to a heptane chain with two unsaturated carbonyl groups that join the structure (Zhai et al., 2020). The most commonly found type of curcumin in Temulawak is *dicinnamoylmethane* derivatives. However, other types such as *octahydrocurcumin*, *dihydrocurcumin*, *hexahydrocurcumin*, curcumin, and *monodemethoxy* curcumin can also be found (Rahmat et al., 2021).

Characteristics of temulawak and curcumin

Temulawak (*Curcuma xanthorrhiza*) is a plant in the *Curcuma* genus and the *Zingiberaceae* family, typically found in tropical rainforests. Regionally, it is known as koneng gede in Sundanese, temu labak in Madurese, tommo in Bali, tommon in South Sulawesi, and karbanga in Ternate (Ningrum et al., 2023). In Indonesia, this plant is often cultivated for its medicinal properties. Temulawak has numerous bioactive compounds and secondary metabolites often used as medicine (Syamsudin et al., 2019). It has a dark yellow or slightly brown exterior and a yellow-orange interior. While frequently confused with turmeric (*Curcuma longa* L.), the two differ significantly in physical structure. Specifically, *C. xanthorrhiza* produces a large, oval, egg-like parent rhizome with elongated branches, whereas *C. longa* typically has more slender, finger-like branches (Rahmat et al., 2021).

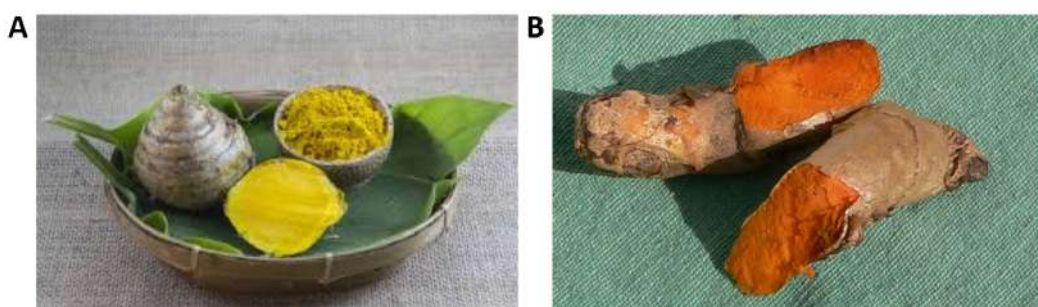


Figure 1. Side-by-side comparison of *Curcuma xanthorrhiza* (Temulawak) and *Curcuma longa* L. (Turmeric) rhizomes. (A) by Herusutimbul (2021) and (B) by Ulrich Prokop (2007). Both images are reprinted from Wikimedia Commons under CC BY-SA 4.0/3.0.

Beyond its physical appearance, temulawak has a slightly bitter, spicy, and earthy flavor when consumed. Normally, it can be used as a spice to enrich the flavor of dishes. Temulawak can also be processed into a medicinal herbal product. The bioactive compounds can also be extracted from temulawak and consumed as supplements. Curcumin contributes to the yellow color in temulawak, making it a valuable natural dye. Moreover, it acts as an antioxidant that helps to prevent oxidative damage (Jakubczyk et al., 2020). The antioxidant properties of curcumin also help to maintain a healthy liver and prevent hepatocyte damage (de Porras et al., 2023). Other than acting as an antioxidant, curcumin also provides anti-inflammatory and antibacterial properties (Mucha et al., 2021).

Analysis method to identify curcumin

The overall curcumin concentration in temulawak is 2.3% (Mukti & Hermady, 2020). The concentration of curcumin in temulawak can be determined by laboratory analysis such as high-performance liquid chromatography (HPLC). HPLC separates and precisely quantifies individual compounds in a mixture, allowing specific measurement of the amount of curcumin present. HPLC utilizes a C18 column with 425 nm UV detection. The mobile phase consists of a mix of acetonitrile and water (50:50 v/v) that has been acidified with 2% acetic acid, with a flow rate of 1.2 mL/min (Fonseca-Santos et al., 2017). Curcumin is less volatile; therefore, gas chromatography is not commonly used to analyze curcumin levels (Kotra et al., 2019).

Chemical and physical stability of curcumin

Several external factors may influence curcumin stability. It is a hydrophobic compound with limited solubility in water, particularly under acidic conditions (Zheng & McClements, 2020). The environment's pH strongly influences curcumin, as pure curcumin is unstable under alkaline conditions and crystallizes out

under acidic conditions (Kharat et al., 2017). Light also affects curcumin stability. Light exposure alters the chemical structure of curcumin by combining the hydrolytic and oxidative fragments of the heptadienone moiety, which results in degradation (Appendino et al., 2021). On the other hand, curcumin is heat stable, but its stability still depends on temperature and heating duration. Normally, curcumin can tolerate heat ranging from 80 to 85°C (Peram et al., 2017). However, roasting curcumin at 180°C for 70 minutes degrades its compounds. When curcumin degrades, it forms smaller compounds such as vanillin, ferulic acid, and 4-vinyl guaiacol, reducing curcumin's original bioactivity (Esatbeyoglu et al., 2015).

Potential health benefits of curcumin

Curcumin, a major polyphenolic compound derived from the turmeric rhizome, possesses diverse biological effects, including antioxidant, anti-inflammatory, anti-cancer, anti-arthritis, anti-asthmatic, antimicrobial, antiviral, and antifungal activities (Kamal et al., 2021). However, its effectiveness is limited due to poor bioavailability, as it is poorly absorbed, rapidly metabolized, and quickly excreted (Liu et al., 2022). To improve its efficacy, curcumin is often paired with absorption enhancers like piperine, which significantly boosts its uptake (Tabanelli et al., 2021). Moreover, curcumin has been found to help reduce exercise-induced inflammation and muscle soreness, leading to faster recovery and enhanced physical performance, making it beneficial for athletes and physically active individuals (Hewlings & Kalman, 2017). All benefits discussed below are summarized in **Table 1**.

Antioxidant benefits of curcumin

Additionally, Consoli et al. (2021) confirmed that curcumin enhances the expression of heme oxygenase-1 (HO-1), an enzyme involved in heme degradation that produces biliverdin, iron, and carbon monoxide, which collectively provide cytoprotective effects against oxidative stress. Furthermore, beneficial outcomes were observed when using curcuminoid mixtures, particularly curcumin-95, which is commonly included in nutritional supplements. Research by Tabanelli et al. (2021) demonstrated that treating astrocytes with curcumin at concentrations of 5–15 μ M significantly increased HO-1 expression.

Curcumin works as an antioxidant by scavenging reactive oxygen species and interrupting lipid peroxidation. The methoxyphenol group in curcumin's chemical structure enables hydrogen atom donation to neutralize the free radicals. This effectively neutralizes superoxide and nitrite radicals, as well as hydrogen peroxide (Anas et al., 2024). This mechanism protects the cells from oxidative stress. Additionally, it can break the 3' position of the free-radical chain, which interrupts the oxidation chain and neutralizes the lipid radicals (Wolnicka-Glubisz & Wisniewska-Becker, 2023). Moreover, curcumin also chelates metals, as it can form complexes with zinc and iron. Forming complexes with zinc increases the stability of free radicals, which prevents oxidative stress. Similarly, iron complexes improve the antioxidant capacity of curcumin (Prasad et al., 2021).

Anti-cancer potential of curcumin

Curcumin exhibits multiple biological activities with chemopreventive and therapeutic properties, suggesting its potential as an anticancer agent (Panda et al., 2017). While many findings have been derived from animal studies, curcumin has also demonstrated effectiveness in various in vitro models at doses comparable to those used in human studies (Lopresti, 2017). In vitro and in vivo research suggests that curcumin inhibits cancer development by targeting two key processes: angiogenesis and tumor growth (Wang et al., 2017).

Furthermore, Moghaddam et al. (2019) suggest that curcumin has a biphasic effect on the proteasome, activating it at low concentrations while inhibiting it at higher doses. Additionally, proteasome

activation supports cell survival, whereas inhibition triggers apoptosis, meaning curcumin's effects depend on the dosage. Additionally, its concentration determines the type of cell death it induces. Lower doses increase oxidative stress and promote apoptosis, while higher doses reduce reactive oxygen species (ROS) production, deplete ATP levels, and cause necrotic cell death (Zhong et al., 2016). This dual mechanism suggests that curcumin may play a significant role in protecting against neurodegenerative conditions, such as Alzheimer's disease, by regulating cell survival and death pathways (Ghosh et al., 2015). Curcumin interferes with the EGFR cell signaling pathway, which is associated with cancer cell proliferation, adhesion, migration, and differentiation. By reducing EGFR and Akt levels, curcumin disrupts breast cancer cell formation. Moreover, curcumin modulates Nrf2 transcription factors that detoxify and neutralize ROS, lowering cancer risk (Giordano & Tommonaro, 2019).

Neuroprotective and cognitive benefits of curcumin

Curcumin has demonstrated significant neuroprotective properties, making it a promising natural compound for preventing and managing neurodegenerative diseases such as Alzheimer's disease, Parkinson's disease, and multiple sclerosis (Adami & Bottai, 2020). Its neuroprotective effects primarily stem from its anti-inflammatory, antioxidant, and anti-apoptotic mechanisms (Guo et al., 2020). Curcumin reduces neuroinflammation by inhibiting key inflammatory pathways, such as NF- κ B and pro-inflammatory cytokines (TNF- α , IL-6, IL-1 β), which contribute to neuronal damage and cognitive decline (Gao et al., 2019). Additionally, its antioxidant properties help neutralize reactive oxygen species (ROS) and free radicals, preventing oxidative stress, which plays a critical role in neurodegeneration (Silvestro et al., 2021).

Perrone et al. (2015) investigated the potential of curcumin in preventing neurodegenerative diseases, particularly Alzheimer's disease. Given that oxidative damage and inflammation are significantly elevated in the brains of Alzheimer's patients, the aqueous extract of turmeric, which possesses antioxidant properties, may be beneficial for long-term therapy (Simunkova et al., 2019). Chronic curcumin treatment at 5 and 10 mg/kg reversed all negative physiological and performance changes caused by stress induction in humans (Oliveira & Pieniz, 2024). Since the buildup of amyloid-beta (A β) plaques is a defining characteristic of Alzheimer's disease (AD), curcumin has been explored for its potential role in preventing their formation and accumulation. Research using AD mouse models has demonstrated that administering curcumin via the intragastric route significantly reduces A β production (Tang & Taghibiglou, 2017). This occurs through the downregulation of BACE1 expression, an enzyme that cleaves amyloid precursor protein (A β PP) into A β peptides, thereby limiting plaque formation (Orobets & Karamyshev, 2023). Moreover, curcumin-treated rats showed reduced synaptic degradation, a critical factor in AD-associated cognitive decline. As a result, these animals showed notable improvements in spatial learning and memory performance, suggesting curcumin's neuroprotective effects and its potential as a therapeutic agent for AD (Bassani et al., 2017).

Ferreira et al. (2019) suggest that curcumin can bind to amyloid-beta proteins, preventing their aggregation and promoting clearance from the brain. This helps slow down disease progression and preserve neuronal function. Curcumin also enhances brain-derived neurotrophic factor (BDNF), a key protein involved in neuronal survival, growth, and synaptic plasticity (Jin et al., 2022). Reduced BDNF levels are associated with neurodegenerative conditions and depression, and curcumin supplementation has been found to restore BDNF levels, promoting brain cell regeneration and repair (Bhat et al., 2019). Furthermore, curcumin's ability to modulate neurotransmitters such as serotonin and dopamine contributes to its potential use in treating mood disorders, depression, and anxiety (Lopresti, 2022). Despite its promising benefits, curcumin's poor bioavailability remains a challenge, and combination with piperine (black pepper extract) or liposomal formulations can improve brain absorption (Nugroho et al., 2023).

Antibacterial and antifungal properties of curcumin

In addition to its antioxidant and anti-inflammatory properties, curcumin exhibits significant antibacterial and antifungal activities, which make it known as a potential natural antimicrobial agent. Studies have demonstrated that curcumin has excellent antimicrobial effects against both Gram-positive and Gram-negative bacteria, particularly *Staphylococcus aureus* and *Escherichia coli* (Dai et al., 2022). The antibacterial mechanism of curcumin involves disruption of the bacterial cell membrane, leading to increased membrane permeability and leakage of intracellular contents. Furthermore, curcumin has been shown to inhibit the synthesis of bacterial virulence factors, suppress biofilm formation, and interfere with quorum-sensing pathways, which are critical for bacterial pathogenicity and resistance development. At the molecular level, curcumin has been reported to interfere with bacterial DNA replication, alter plasmid gene expression, and suppress bacterial motility, thereby impairing the ability of bacteria to proliferate and colonize host tissues (Hussain et al., 2022; Adamczak et al., 2020). These multiple modes of action contribute to its efficacy and reduce the likelihood of resistance development, a key limitation of conventional antibiotic therapy.

Curcumin also exhibits notable antifungal activity, with evidence indicating its capacity to inhibit the growth of several pathogenic fungi, including *Candida albicans* and *Aspergillus* spp. The primary mechanism involves disruption of ergosterol biosynthesis, an essential component of fungal cell membranes. This disruption compromises membrane integrity and function, ultimately leading to cell death (Chen et al., 2016). Additionally, curcumin has been shown to induce reactive oxygen species (ROS) production within fungal cells, increasing oxidative stress and contributing to cellular damage and apoptosis. Another study also suggests that curcumin can act synergistically with conventional antibiotics and antifungal agents, enhancing their efficacy and potentially reducing the required therapeutic dosage. This synergistic effect not only improves antimicrobial outcomes but may also mitigate the development of antimicrobial resistance (Adamczak et al., 2020).

Anti-inflammatory effects of curcumin

Curcumin reduces inflammation, pain, and swelling in various chronic inflammatory conditions, including rheumatoid arthritis (RA), asthma, and other autoimmune disorders. In RA, curcumin downregulates various signaling pathways, including mitogen-activated protein kinases (MAPKs) such as p38 MAPK and extracellular signal-regulated kinase (ERK). It also suppresses various transcription factors, such as nuclear factor kappa B (NF- κ B) and activator protein-1 (AP-1), which are involved in the inflammatory cascade (Dehzad et al., 2023). By inhibiting these pathways, curcumin inhibits the expression of proinflammatory cytokines, such as tumor necrosis factor-alpha (TNF- α), interleukin-6 (IL-6), and interleukin-17 (IL-17), thereby reducing joint inflammation and tissue destruction associated with RA. Furthermore, curcumin has been reported to modulate the PI3K/Akt signaling pathway, which plays a key role in immune cell survival, proliferation, and cytokine production (Kou et al., 2023).

Aside from suppressing rheumatologic conditions, curcumin also shows promising effects in the prevention and management of asthma. Asthma is a chronic inflammatory disorder that is characterized by reversible airway obstruction, bronchial hyperresponsiveness, and infiltration of immune cells such as eosinophils and T-helper 2 (Th2) lymphocytes, causing breathing difficulty (Hashmi & Cataletto, 2024). Similarly, curcumin mitigates asthma pathophysiology by suppressing Th2-mediated immune responses and reducing the expression of cytokines such as IL-4, IL-5, and IL-13, the main mediators of eosinophilic inflammation and IgE production. Additionally, curcumin decreases TNF- α levels that are responsible for airway remodeling and hyperresponsiveness. Zhu et al. (2019) also demonstrated that curcumin

consumption significantly reduced airway inflammation, decreased eosinophil infiltration, and restored normal lung histopathology in asthma animal models.

A randomized controlled study by Quan et al. (2021) also supports curcumin's anti-inflammatory activity. This study reports that an oral dose of 3000 mg of curcumin daily over several weeks significantly improved asthma control by reducing serum levels of inflammatory biomarkers and enhancing pulmonary function. These effects are attributed to curcumin's ability to regulate immune responses and oxidative stress, which play a key role in asthma pathogenesis. Moreover, curcumin suppresses pro-inflammatory eicosanoids, such as prostaglandins and leukotrienes, further enhancing its role in resolving chronic inflammation. It also modulates cyclooxygenase-2 (COX-2) and lipoxygenase (LOX) enzyme activity, which are involved in arachidonic acid metabolism and inflammation. Overall, these multi-targeted mechanisms highlight the therapeutic potential of curcumin as an anti-inflammatory agent in both systemic and localized inflammatory conditions. Despite these promising outcomes, curcumin's clinical efficacy is still limited due to its low bioavailability. This includes the use of bioenhancers like piperine or formulation improvements through nanocarriers and liposomal delivery systems. These approaches have been shown to significantly increase systemic curcumin concentrations, enhancing its anti-inflammatory efficacy in clinical settings.

Table 1. Summary of health properties and biological mechanisms of curcumin

Health Benefit	Study Model	Primary Mechanism	References
Antioxidant	Astrocytes; General cellular models	Scavenges ROS; Interrupts lipid peroxidation; Induces HO-1 expression; Chelates metal (Zn & Fe)	Consoli et al. (2021); Anas et al. (2024); Prasad et al. (2021)
Anti-cancer	In vitro (breast cancer); In vivo (animal models)	Inhibits angiogenesis and tumor growth; Modulates EGFR/Akt pathways; Biphasic effect of proteasomes; Activates Nrf2	Panda et al. (2017); Wang et al. (2017); Moghaddam et al. (2019); Zhong et al. (2016)
Neuroprotective	AD Mouse models; Rats; Human stress induction	Reduces neuroinflammation (NF- κ B); Downregulates BACE1; Reduces A β plaques; Enhances BDNF levels; Modulates serotonin/dopamine	Adami & Bottai (2020); Tang & Taghibiglou (2017); Bassani et al. (2017); Jin et al. (2022)
Antibacterial	<i>S. aureus</i> ; <i>E. coli</i>	Disrupts bacterial cell membranes; Inhibits biofilm formation and quorum sensing; Interferes with DNA replication and motility	Dai et al. (2022); Hussain et al. (2022); Adamczak et al. (2020)

Health Benefit	Study Model	Primary Mechanism	References
Anti-fungal	<i>Candida albicans</i> ; <i>Aspergillus spp.</i>	Disrupts ergosterol biosynthesis in cell membranes; Induces ROS production leading to apoptosis; Works synergistically with antifungals	Chen et al. (2016); Adamczak et al. (2020)
Anti-inflammatory (RA & Asthma)	Human (Clinical trials); Asthma animal models	Downregulates p38 MAPK, ERK, and NF-κB; Suppresses pro-inflammatory cytokines (TNF-α, IL-6, and IL-17); Modulates COX-2 and LOX enzymes	Dehzad et al. (2023); Zhu et al. (2019); Quan et al. (2021)

Safety and efficacy

Curcumin, the active compound found in temulawak, has been widely studied for its therapeutic potential in both animal and human health (Sharifi-Rad et al., 2020). It exhibits anti-inflammatory, antioxidant, antimicrobial, and anticancer properties, making it a promising natural compound for various diseases. Moreover, its safety and efficacy depend on factors such as dosage, bioavailability, and long-term effects (Tabanelli et al., 2021).

Curcumin safety and efficacy in human beings

The U.S. Food and Drug Administration (FDA) classifies curcumin as Generally Recognized as Safe (GRAS) for human consumption (Pancholi et al., 2021). Clinical studies have demonstrated that oral doses of up to 8 grams per day over several months are generally well tolerated, with no evidence of severe toxicity. Nonetheless, some individuals may experience mild side effects, including gastrointestinal discomfort, nausea, diarrhea, or headaches. While short-term safety is well established, the long-term effects of high-dose curcumin supplementation remain uncertain. High intake may interfere with iron absorption, alter liver enzyme activity, and potentially interact with anticoagulant medications, thus necessitating caution in specific populations (Zielinski et al., 2015).

Badan Pengawas Obat dan Makanan (BPOM) regulates curcumin and temulawak-derived products in Indonesia under its traditional medicine and supplement framework. According to BPOM Regulation No. 12 of 2014 on Traditional Medicine, curcumin from temulawak (*Curcuma xanthorrhiza*) extract is permitted as an ingredient in *jamu*, herbal supplements, and functional food products, provided it meets quality, safety, and efficacy standards. Products containing curcumin must comply with limits on several indicators, such as heavy metals, microbial contamination, and pesticide residues, and manufacturers must submit preclinical and clinical data demonstrating safety if the product makes health claims beyond general wellness. Furthermore, BPOM Decree No. HK.00.05.41.1381 (2005) includes temulawak as an approved herbal material for traditional medicine, and it may be used in registered standardized herbal products (OHT) or phytopharmaca, provided it follows scientific validation.

Human studies suggest that curcumin may be effective in the management of osteoarthritis, metabolic syndrome, and inflammatory bowel diseases, offering potential alternatives or adjuncts to conventional therapies (Peng et al., 2021). Several clinical trials also report benefits in reducing systemic inflammation, lowering LDL cholesterol, and improving cognitive performance, particularly in older adults or

those with neuroinflammatory conditions. However, despite promising evidence, curcumin's therapeutic utility is limited by its poor oral bioavailability, largely due to its low solubility, rapid metabolism, and systemic elimination. As a result, variability in clinical outcomes remains a concern, prompting the development of advanced delivery systems such as nanoparticles, liposomes, phospholipid complexes, and co-administration with bioenhancers like piperine to optimize its pharmacokinetic profile.

Curcumin safety and efficacy in animals

Curcumin is considered a non-toxic feed additive that enhances immunity, growth performance, and behavior in poultry (Pan et al., 2022). Additionally, it provides liver protection by preventing oxidative damage and disrupting lipid metabolism, primarily through its effects on the intestinal microbiota (Zhai et al., 2020). Studies in rodents also show that curcumin is well tolerated, with no significant toxicity observed at doses up to 12 g/kg body weight in short-term studies. However, prolonged high-dose consumption may cause gastrointestinal (GI) issues, liver dysfunction, and oxidative stress in some cases.

In animal studies, both temulawak and curcumin have shown strong pharmacological effects with a good safety profile. Research in rodents and other animal models has demonstrated their anti-inflammatory, hepatoprotective, and antioxidant properties, supporting their traditional use (Memarzia et al., 2021). Temulawak extracts have been tested in rats and mice and were found to improve liver function, reduce oxidative stress, and promote digestive health without significant toxicity at normal doses (Rosidi et al., 2024). However, extremely high doses may alter liver enzymes, indicating that excessive consumption should be avoided (Farzaei et al., 2018).

Moreover, animal research has shown curcumin's therapeutic potential in treating neurological disorders (e.g., Alzheimer's disease), metabolic conditions (e.g., diabetes), cardiovascular diseases, and cancer. It has been found to reduce inflammation, oxidative stress, and tumor growth, while also boosting immune function and gut health. However, its poor bioavailability due to low absorption and rapid metabolism remains a challenge. To improve its effectiveness, researchers are investigating nanoformulations and bioenhancers such as piperine (Salsabila et al., 2021).

TECHNOLOGY DEVELOPMENT

Industrial extraction of curcuminoids

The production of high-purity pharmaceutical ingredients from plant-based raw materials requires specialized extraction techniques. While traditional sun-drying and grinding are sufficient for domestic or localized production, industrial and pharmaceutical applications require standardized yields. Over the years, industrial processing of plant materials has typically used conventional thermal methods such as Soxhlet extraction, water distillation extraction, and steam distillation. However, these processing methods often rely on large volumes of solvents and high temperatures, which are highly correlated with thermal degradation of bioactive compounds and high energy consumption. This often leads to unsustainable practices. To overcome these limitations, recent industrial processing has started to shift towards the utilization of Ultrasonic-Assisted Extraction (UAE) methods. According to Shen et al. (2023), UAE is considered an environmentally friendly and efficient extraction method that reduces organic solvent usage, thus reducing environmental impact.

Specifically, recent advancements have focused on optimizing parameters associated with curcuminoid recovery. Following the procedure optimized by Yusnira & Ediputra (2025), the extraction process begins with raw material preparation. *Curcuma* rhizomes will be ground, sieved, and stored in airtight containers under dry conditions. Following this, a preliminary extraction will be conducted using a

UAE method with a power range of 100–400 W, an extraction time of 10–60 minutes, and a material-to-solvent ratio of 1:10 to 1:40 g/mL, utilizing ethanol concentrations between 50–95%. The ethanol solvent will be added to the *Curcuma* powder, and the mixture will be processed using an ultrasonic processor. During this stage, the mixture will be kept at a controlled temperature of $30\pm 2^{\circ}\text{C}$ using a water bath. Finally, the mixture will be filtered using Whatman No. 1 filter paper and concentrated using a rotary evaporator at 50°C to yield a high-purity extract suitable for further application.

Compared with traditional methods, the UAE method shows better efficiency and productivity. Based on the current data, the UAE method yields 8.4 times more curcuminoids in a shorter extraction time of 52 minutes. Beyond its yield, the UAE method also provides an advantage in the preservation of curcuminoid quality ($\text{IC}_{50} = 31.2 \mu\text{g/mL}$); this is due to its low operating temperature of $30\pm 2^{\circ}\text{C}$, which prevents thermal degradation.

Spray-dried microencapsulation of curcumin from temulawak

Temulawak is an herb that thrives in Indonesia and is known for its pharmaceutical properties in treating various diseases like liver disorder, constipation, bloody diarrhea, hemorrhoids, and skin irritation (Nurcholis et al., 2018). The main bioactive compound in temulawak is curcumin, which can be extracted from its roots and has strong antibacterial properties (Lee et al., 2017). However, curcumin has several limitations, such as low solubility in water, thermal instability, and limited bioavailability (Tabanelli et al., 2021). Yonata et al. (2025) used microencapsulation to trap curcumin in one or more layers of wall material. The wall materials used were maltodextrin (MDE), gum arabic (GAR), and whey protein isolate.

Furthermore, an additional composite wall material, namely β -cyclodextrin (βCD), was used. Their study showed that microencapsulation prepared in a single-wall material shows irregular shapes and rough surfaces. Meanwhile, those with additional composite materials had smoother particles with increased stability during storage relative to temperature and pH. The addition of composite material in microencapsulation can act as emulsifiers, matrix formers, and fillers (Lara-Espinoza et al., 2018). Similarly, research on ginger spray drying by Fernandes et al. (2016) found that homogenization and ultrasonication improved retention of volatile compounds. Additionally, using maltodextrin as a secondary wall material in microencapsulation protects the encapsulated core materials, has low viscosity at high solid concentrations, and has a neutral aroma and taste. Hence, this method may be attempted on curcumin to find a more stable and effective microencapsulation. Microencapsulation is useful at an industrial scale and can increase nutritional value, mask unpleasant taste, and extend shelf life (Peanparkdee et al., 2016). Therefore, microencapsulating curcumin shows great potential for future applications in the pharmaceutical industry to provide greater stability, bioavailability, and effectiveness.

Curcumin nanophytosomes

The demand for drug-resistant malaria has been increasing over the years, as routine therapy has shown unsatisfactory results. According to Alam et al. (2016), curcumin has effective antimalarial properties in treating drug-resistant malaria. Moreover, adding chondroitin sulfate, a carbohydrate polysaccharide, has shown promising effects as an inhibitory antimalarial agent (Clark, 2019). Research by Bhargav et al. (2023) found that combining curcumin with chondroitin sulfate into nano-phytosomes has proven to treat drug-resistant malaria. Furthermore, it was mentioned that these curcumin nano-phytosomes are considered an affordable product for society and can be taken orally. Curcumin and chondroitin sulfate work together to target the ring stage of the parasite, leading to extracellular and intracellular destruction of malarial parasites (Borgheti-Cardoso et al., 2020).

Optimization of curcumin and turmerone in reducing skin irritation

Curcumin is known for its therapeutic components, such as antioxidant, anti-inflammatory, antimicrobial, anti-cancer, and wound-healing properties (Kumari et al., 2022). On the other hand, turmerone is a key component found in turmeric and has therapeutic properties, such as antioxidant, anti-tumor, anti-cancer, and inflammatory management (Shahrajabian & Sun, 2024). The combination of curcumin and turmerone has been shown to have a better anti-inflammatory effect than curcumin alone (Toden et al., 2017). Skin irritation occurs when a person is exposed to extrinsic factors (e.g., UV radiation, microbial infection), intrinsic factors (e.g., allergies, autoimmune responses), or both (Novak-Bilić et al., 2018). This impaired barrier function can lead to dryness, itchiness, redness, flakes, and a rough texture (Yosipovitch et al., 2019). Aydin et al. (2024) combined curcumin and turmerone as solid lipid nanoparticles using nanoencapsulation. The process used to nano-encapsulate these compounds is hot homogenization and ultrasonication. The results showed that curcumin and turmerone solid lipid nanoparticles remained stable for 60 days under controlled conditions. Hence, these solid lipid nanoparticles designed for topical delivery reduced inflammation and may have potential for future therapeutic applications.

Active compounds in temulawak for cancer prevention

Temulawak has been used as a medicinal herb in Indonesia for a long time. It contains several bioactive compounds such as curcuminoids, xanthorrhizol, phelandrene, camphor, tumerol, and more (Novianti & Kartika, 2019). This herb has been used to treat gastrointestinal (GI) disease, boost immunity, and maintain overall health (Surya et al., 2024). Curcumin, as one of its main bioactive compounds, serves many health benefits, like antibacterial, antioxidant, anti-inflammatory, and anticancer properties. Cancer is caused by genetic or epigenetic alterations in somatic cells, which lead to abnormal cell growth throughout the body (Saini et al., 2020). A study conducted by Ali et al. (2022) shows the potential of curcumin as an anticancer agent. The research showed that curcumin can inhibit nuclear factor-kappa B (NF- κ B) and disrupt glycation by triggering harmful molecules involved in inflammation and mutations. Moreover, curcumin can actively inhibit the growth of B3 epithelial lens cells in humans induced by rhbFGF. Overall, curcumin has shown great potential in inhibiting cancer growth.

Curcumin as a smart and active biodegradable polymer-based film

From a food quality control perspective, packaging is considered an important part of a process in protecting foods from external sources like light, gas, moisture, microbes, and temperature (Viscusi et al., 2025). With rising demand for biodegradable, sustainable, and fresh food packaging, food industries are slowly shifting towards more sustainable packaging. Active packaging incorporates bioactive compounds into packaging to improve the quality and safety of packaged food (Wadud et al., 2022). Furthermore, smart packaging reacts to the inner atmosphere of the packaging, which acts as a sensor to show changes inside the product or the atmosphere (Schaefer & Cheung, 2017). Based on research conducted by De Oliveira Filho et al. (2021) found that curcumin acts as a bioactive compound that can be extracted and implemented as a smart and active edible bioactive film. Curcumin, a natural pigment found in turmeric, is highly sensitive to acids and bases, making it an effective pH indicator in smart packaging (Roy et al., 2022). Due to its high sensitivity, the curcumin molecule undergoes visible color changes as pH shifts. Therefore, consumers can detect food spoilage immediately without opening the package (El-Saadony et al., 2023). Additionally, curcumin is a natural bioactive compound; hence, implementation of curcumin into smart packaging is safe to consume (Oliveira Filho & Egea, 2022). However, further research should be done to ensure the stability of the compound by utilizing micro- and nanoencapsulation during digestion.

FUTURE OUTLOOKS

Due to its multifunctional properties, curcumin shows great potential for future applications in various industries. Curcumin is widely known for its health benefits, such as anti-inflammatory, antimalarial, antibacterial, anticancer, and more. Moreover, curcumin has potential for use in smart and active packaging to improve food safety and shelf life.

However, several issues still require further research. For instance, curcumin is naturally unstable; therefore, further research on micro- and nanoencapsulation methods is necessary to increase its stability, solubility, and bioavailability in smart packaging (Chen et al., 2020). Additionally, regulatory guidelines must be established to ensure the safety, consistency, and efficiency of curcumin-based products before industries use them widely (Jacob et al., 2024). Further research can explore its therapeutic effects in pharmaceuticals and functional foods, such as enhanced absorption and targeted delivery. It is anticipated that curcumin's use in sustainable packaging, healthcare, and product development will increase dramatically as food science, nanotechnology, and biomedicine continue to grow.

CONCLUSION

Curcumin is the primary bioactive compound in temulawak (*Curcuma xanthorrhiza*) and offers several health benefits, including antioxidant, anti-inflammatory, antimicrobial, and anticancer properties. Moreover, curcumin can be used for various applications in functional foods, pharmaceuticals, and biodegradable packaging. Despite its benefits, curcumin is known for its low solubility and instability. To overcome these challenges, researchers have increasingly focused on nanoencapsulation, microencapsulation, and phytosome technology to improve stability and absorption of its therapeutic potential.

As research on curcumin expands, regulatory guidelines will be crucial for future industrial applications. Future studies should focus on enhancing solubility, optimizing delivery mechanisms, and integration into sustainable and active formulations. By addressing these challenges, curcumin from temulawak shows a promising role in medicine, food technology, and environmentally friendly products.

AUTHOR CONTRIBUTIONS

EP: Conceptualization, Investigation, Writing - Original Draft. **JCT:** Conceptualization, Investigation, Writing - Original Draft. **KAT:** Investigation, Formal Analysis, Writing - Original Draft. **NN:** Investigation, Formal Analysis, Writing - Original Draft. **LJ:** Supervision, Writing - Review & Editing.

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COMPETING INTERESTS

The authors declare no known competing financial interests or personal relationships that could have an impact on the work reported in this paper.

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