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REVOLUTIONIZING CURCUMIN BIOAVAILABILITY: FROM HEALTH BENEFITS TO PLACEMENT IN FOOD PACKAGING PRODUCTS

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KEY WORDS:
Curcumin, delivery system, encapsulation, packaging, human health

ABSTRACT

Curcumin, the principal bioactive compound in turmeric (*Curcuma longa* L.), is widely recognized for its pharmacological properties, including antioxidant, anti-inflammatory, and anticancer activities. However, its low bioavailability remains a major obstacle in the development of curcumin-based applications in food and pharmaceutical sectors. This review provides a comprehensive overview of recent technological advancements aimed at enhancing curcumin's bioavailability, including encapsulation techniques, lipid-based delivery systems, and chemically modified curcumin derivatives. These innovations have demonstrated significant potential in improving the solubility, stability, and absorption of curcumin in the human body. Furthermore, recent trends in research utilizing natural carriers such as plant-derived proteins and polysaccharides are discussed, aligning with sustainable and food-safe delivery approaches. The review emphasizes an interdisciplinary approach that integrates food material science, biodegradable packaging, bioactive compound chemistry, and nanotechnology engineering. As formulation technologies continue to evolve, the application of curcumin in functional foods and health supplements becomes increasingly promising. The article also highlights existing research gaps and future directions, focusing on biological efficacy, long-term safety, and production scalability. This review aims to serve as a valuable reference for researchers and industry stakeholders in accelerating the utilization of curcumin through effective and sustainable smart delivery systems.

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РЕВОЛЮЦИЯ В БИОДОСТУПНОСТИ КУРКУМИНА: ОТ ПОЛЬЗЫ ДЛЯ ЗДОРОВЬЯ ДО ПРИМЕНЕНИЯ В УПАКОВОЧНЫХ МАТЕРИАЛАХ ДЛЯ ПИЩЕВЫХ ПРОДУКТОВ

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КЛЮЧЕВЫЕ СЛОВА:
куркумин, система доставки, инкапсуляция, упаковка, здоровье человека

АННОТАЦИЯ

Куркумин, основное биоактивное вещество куркумы (*Curcuma longa* L.), широко известен своими фармакологическими свойствами, включая антиоксидантную, противовоспалительную и противораковую активность. Однако его низкая биодоступность остается серьезным препятствием для разработки продуктов на основе куркумина в пищевой и фармацевтической промышленности. В настоящей работе представлен всесторонний обзор последних технологических достижений, направленных на повышение биодоступности куркумина, включая методы инкапсуляции, системы доставки на основе липидов и химически модифицированные производные куркумина. Эти инновации продемонстрировали значительный потенциал в улучшении растворимости, стабильности и усвоения куркумина в организме человека. Кроме того, обсуждаются последние тенденции в исследованиях с использованием натуральных носителей, таких как растительные белки и полисахариды, в соответствии с подходами к устойчивой и безопасной для пищевых продуктов доставке. В обзоре подчеркивается междисциплинарный подход, объединяющий науку о пищевых материалах, биоразлагаемую упаковку, химию биоактивных соединений и нанотехнологическую инженерию. По мере развития технологии рецептур применение куркумина в функциональных продуктах питания и биологически активных добавках становится все более многообещающим. В статье также освещаются существующие пробелы в исследованиях и будущие направления, с упором на биологическую эффективность, долгосрочную безопасность и масштабируемость производства. Целью этого обзора является предоставление ценного справочного материала для исследователей и представителей отрасли для ускорения использования куркумина с помощью эффективных и устойчивых интеллектуальных систем доставки.

ФИНАНСИРОВАНИЕ: Это исследование спонсируется Программой Rumah (RP) Исследовательской организации по сельскому хозяйству и продовольствию (ORPP) BRIN TA 2025 № B-34668/III.11/TK.01.02/12/2024 для серии исследований, связанных с куркумином и его применением в биоразлагаемой упаковке/биопленке.

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1. Introduction

Food preservation and packing depend heavily on packaging [1]. Nevertheless, though it serves its primary function, the majority of the materials utilized in its production are petroleum-based plastic. Plastic is often thought to be non-biodegradable and challenging to recycle, both having an adverse effect on the environment [2]. The unchecked buildup of plastic garbage in nature, particularly in marine environments, upsets the species' biological balance and raises pollution levels [3]. The development of more effective recycling techniques is required to reduce the adverse environmental effects of food packaging. To develop biodegradable packaging materials that are effective at protecting food while also having little to no adverse environmental effects, new alternatives must be found.

The scientific community is becoming more interested in edible or biodegradable biopolymer packaging as a non-toxic and biodegradable substitute for organically derived polymers [4]. Thin coatings of food-derived compounds called edible films act as a barrier to keep out gases, moisture, and solutes in meals [5]. In addition to providing passive protection, edible food packaging can also be used to bioactively carry substances that are critical to human health [6]. A new type of edible food packaging has emerged in recent years, incorporating functional elements that may improve consumers' health [7]. Curcumin is regarded as a nontoxic and edible substitute [8]. This material has the ability to prolong shelf life and can be used to track the freshness of food items [9].

The primary ingredient in turmeric, curcumin, may find use in a number of conventional medications as well as in packaging [10]. The packaging industry is increasingly using this bioagent, which is mostly produced in India, because of its non-toxic nature, film-forming capabilities, and UV barrier qualities [11]. Curcumin is a very sensitive substance that can be used as an indication in smart packaging, since it becomes yellow at neutral and acidic pH values between 1 and 7 and red at alkaline pH values above 8.5 [12]. The creation of composite films using curcumin in food packaging is intriguing since it offers extra functional qualities including enhanced mechanical strength, UV protection, antioxidant qualities, and antibacterial activity [13]. As a result, adding curcumin to packaging methods enhances food safety and enables consumers to quickly check the freshness of food without the need for complex equipment.

Curcumin has emerged as a lucrative option for the production of active compounds in this context [10]. Nevertheless, there are numerous restrictions on curcumin's ability to reinforce food packaging. Curcumin's intrinsic hydrophobicity makes it challenging to disperse in a hydrophilic film matrix [14]. However, curcumin's low environmental stability means that it can degrade when exposed to heat and light, which will reduce the final food packaging activity [12]. Encapsulation techniques have emerged as a successful means of getting around these restrictions in recent years. The technique of adding curcumin to other substances, such as niosomes, liposomes, or nanoparticles, is known as curcumin encapsulation [15]. Curcumin's stability, bioavailability, and activity may all be improved by this encapsulation [16]. In this instance, encapsulated curcumin is utilized as an active ingredient in the packaging to extend the product's shelf life and offer further protection or health advantages [17].

An inventive method for creating edible packaging is the use of curcumin as an active ingredient, particularly in the food or pharmaceutical sectors [18]. This review article's goal is to investigate curcumin's potential as a natural ingredient for the creation of active edible packaging, particularly in light of food safety, health effects, and environmental sustainability. Curcumin may offer a more secure and efficient substitute for artificial chemicals.

2. Objects and methods

2.1. Literature search

This review was conducted following a structured approach to ensure comprehensive coverage and relevance of the literature. A systematic literature search was performed using major databases including PubMed, Scopus, Web of Science, and Google Scholar. The search terms used were: “curcumin bioavailability,” “nanotechnology curcumin,” “curcumin health benefits,” “curcumin delivery systems,” “curcumin in food packaging,” and combinations thereof.

2.2. Criteria for inclusion or exclusion

The inclusion criteria were: Articles published in English between 2000 and 2025; Peer-reviewed original research articles, reviews, and book chapters; and Studies focusing on curcumin's bioavailability enhancement, health benefits, delivery systems, and application in food packaging. Exclusion criteria included: Non-English publications; Studies not related to curcumin or its bioavailability; and Conference abstracts without full papers.

2.3. Data sources and geographic information

In total, 98 articles were included after screening more than 300 initial titles and abstracts. Data were extracted based on study design, formulation strategies, observed effects, and relevance to curcumin’s use in food or biomedical applications. Geographic origin of the studies was noted but not restricted, with a focus on globally representative research.

2.4. Research subjects and analysis techniques

The selected literature was then categorized thematically into four main sections: (1) Curcumin’s bioavailability issues and enhancement strategies, (2) Health-promoting properties of curcumin, (3) Curcumin nanoformulations and delivery systems, and (4) Innovative applications in food packaging. A qualitative synthesis was performed to identify trends, research gaps, and technological advancements.

3. General information

3.1. Characteristics

Curcumin (diferuloylmethane), a brilliant orange-yellow polyphenolic compound with the chemical formula $C_{21}H_{20}O_6$ [10], was extracted from

the root of *Curcuma longa*, a member of the Ginger / Zingiberaceae family (Figure 1). This root is abundantly grown in Southeast Asia, China, and India [19]. Curcumin's polyphenolic characteristics allow it to modify some signal transmission paths, resulting in a wide range of antibacterial, anticarcinogenic, antioxidant, and nerve effects [20]. Due to its antioxidant and antibacterial qualities that extend the shelf life of products, curcumin is utilized as a bioagent, and is typically coupled with various polymer and nanoparticle systems that find numerous applications in the food packaging sector [18]. However, the compound has not received approval as a medicinal agent because of its limited bioavailability. The complex's limited bioavailability can be attributed to its insolubility in water, poor absorption, fast metabolism within cells, and instability at physiological pH [21]. According to reports, curcumin is safe and has few negative effects in addition to its many health advantages [22]. The antioxidant effectiveness of individual curcuminoids was tested using in vitro model systems such as linoleic acid peroxidation [23]. Curcumin had the best antioxidant activity among the three curcuminoids: demethoxycurcumin, bisdemethoxycurcumin, and curcumin.

3.2. Chemistry

Diferuloymethane is the chemical name for curcumin, which is also referred to as natural yellow because of its distinctive yellow hue, which makes it a valuable coloring additive for food, cosmetics, textiles, and medications [24]. These polyphenols comprise roughly 2–5 % of turmeric's makeup. Vogel discovered curcumin in 1815, and Daybe crystallized it to determine that it was 1,7-bis(4-hydroxy-3-methoxyphenyl)-1,6-heptadiene-3,5-dione [25]. The feruloyl methane skeleton of curcumin was thoroughly characterized by Lampe and Milobedzka in 1910 [26]. Curcumin is an orange-yellow crystalline powder with a molecular weight of 368.37 g/mol and a melting point of around 183 °C [27]. It is made up of two phenolic rings. It is mainly soluble in organic solvents but has poor solubility in water [28]. The rhizome of *Curcuma longa* is isolated to produce curcumin. The pure form of curcumin [1,7-bis(4-hydroxy-3-methoxyphenyl)-1,6-heptadiene-3,5-dione] is not commercially available due to the high expense and complexity of the process [29]. Instead, it is made up of curcuminoids that are found in nature, namely curcumin I, II, and III: 75–81 % curcumin I, 15–19 % curcumin II (demethoxycurcumin), and 2.2–6.6 % curcumin III (bisdemethoxycurcumin) as the majority of its composition [9] (Figure 2).

3.3. Cultivation

The turmeric plant, or *Curcuma longa*, is grown in several nations, including China, Peru, India, Haiti, Jamaica, and Indonesia [8]. The amount of space used for cultivation and the application of chemical fertilizers, particularly nitrogen and potassium, help boost curcumin levels and vegetative development, respectively, but they also have an impact on the production and quality of the turmeric that is produced [30]. In order to grow well, it needs warm, humid weather and prefers wet, well-drained, non-loamy soil [31]. Dried rhizomes provide an extract that is higher in curcuminoid but lower in oleoresin than fresh rhizomes [32]. It is easier to use dried rhizomes because of their low water content, which protects them against microbial invasion [33]. This spice should be harvested only after the stems and leaves begin to dry up and turn brown, which takes more than seven months [34].

3.4. Extraction

To make yellow turmeric, the rhizomes are dried, cooked, and pounded into a powder before being cleaned with an appropriate solvent [33]. The active curcuminoids are separated by extraction, which yields an oleoresin that contains essential oil, resin, and 2–8 % curcuminoids [35]. Since curcuminoids are insoluble in water, they are often separated using highly soluble organic solvents including methanol, ethanol, and acetone [36]. However, some restrictions dictate that only suitable solvents, including ethanol and isopropyl alcohol, must be used when turmeric extracts and curcuminoids are to be employed in food and medication [37]. As shown in the flow diagram (Figure 3), there are several different extraction techniques that can be applied, including hydrotrophic extraction, Soxhlet extraction, low-pressure solvent extraction, supercritical fluid-based extraction, and microwave-assisted extraction.

Traditional solvent extraction techniques like Soxhlet and low-pressure solvent extraction yield significant amounts of curcuminoid when high solvent-to-raw-material ratios are employed [35]. A higher solvent flow rate restricts the process overall, resulting in a lower yield. The employment of clean technology in supercritical fluid-based extraction is known to save time and solvent usage, but it may have disadvantages because of its high operating pressure system [38]. In comparison, supercritical fluid-based extraction recovered over 90 % of curcuminoids and produced the highest curcumin yield [39].

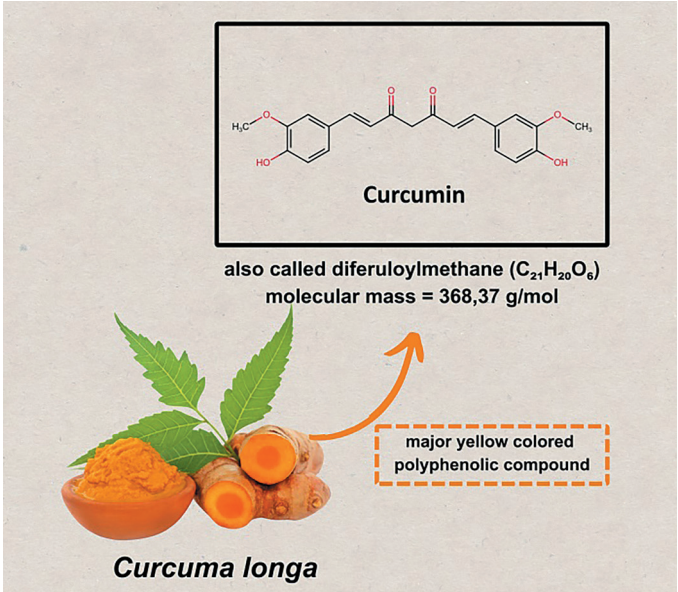

Figure 1. **Chemical structure and appearance of curcumin**
Рисунок 1. **Химическая структура и внешний вид куркумина**

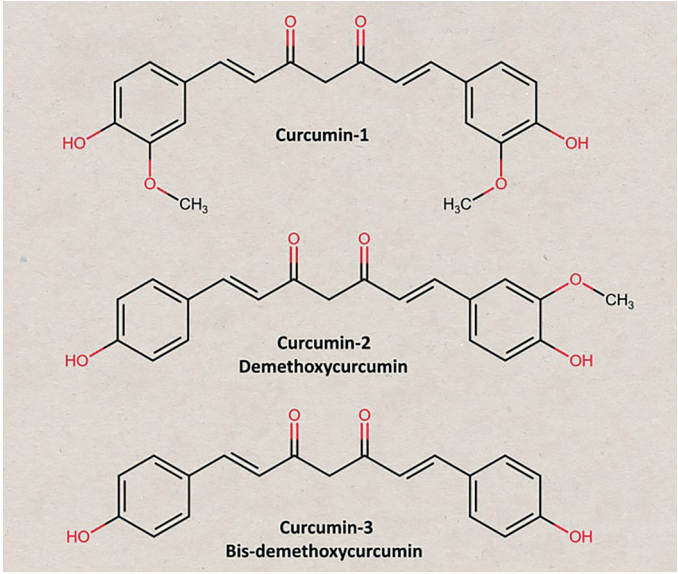

Figure 2. **Curcumin structure**
Рисунок 2. **Структура куркумина**

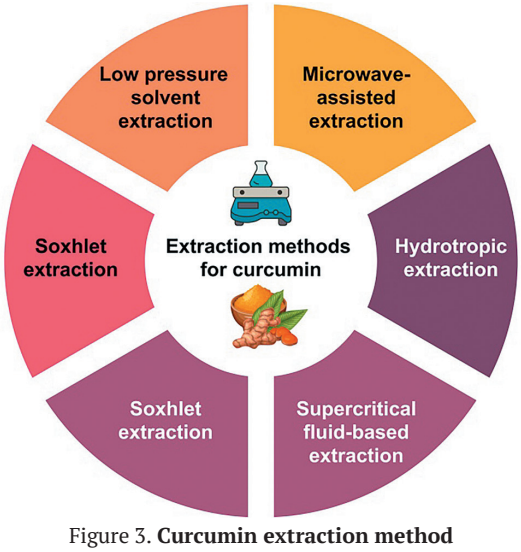

Figure 3. **Curcumin extraction method**
Рисунок 3. **Методы экстракции куркумина**

Organic-solvent-free hydrotrophic process. Hydrotropes and water-soluble organic salts are used in this procedure [40]. Hydrotropes increase the availability of curcuminoids by penetrating the cell walls of turmeric plants and speeding up the dissolution process [41]. Later addition of water results in the precipitation of curcuminoids [42]. Results from this straightforward technique are equivalent to those from other extraction techniques in terms of purity. The turmeric powder and the extraction solvent are heated concurrently using microwave radiation in a dual heating method used in microwave-assisted extraction [43]. Under ideal circumstances, this technique produces higher yields in less time than other conventional extraction techniques.

3.5. Synthesis

Curcumin is made synthetically by starting with vanillin and acetylacetone/B2O3 at room temperature with tributan-2-yl borate and butylamine, and then using ethyl acetate as the solvent [44]. This process yields roughly 80% (Figure 4). Another method for creating curcumin is the Pabon method, which involves condensing acetylacetone and vanillin. The identity of the resultant synthetic compound can be ascertained by comparing its melting point, the melting point of the mixture, and its infrared spectrum to those of the original sample [45]. Over 99.5% curcumin was detected using the rosocyanine technique [46]. Every other chemical utilized in this process is of analytical grade.

3.6. Stability

Curcumin, a bis-α, β-unsaturated β-diketone compound, exists in equilibrium with its enol tautomeric form under various pH conditions [47]. In acidic to neutral environments, the bis-keto form is predominant, whereas at alkaline pH levels (above pH 8), the enol form of the heptadienone chain becomes dominant [48]. Within the pH range of 1 to 7, curcumin typically exhibits a yellow hue, but it undergoes a visible color shift to reddish-orange as the pH exceeds 7.5 (Figure 5). This pH-sensitive color transition, particularly in alkaline conditions, underscores the chemical instability of curcumin and presents a limitation for its use as a colorant in products exposed to basic environments [10]. Empirical data indicate that curcumin is highly unstable between pH 7 and 10, making it more suitable for applications maintained below pH 7. Specifically, in the pH range of 3 to 7, the keto tautomer predominates, while the enol form becomes more prevalent at pH levels above 8 [49].

Curcumin's tautomeric forms, keto and enol, are primarily responsible for its antioxidant activity and phytochemical behavior under physiological settings. These forms engage in free radical scavenging through methods of electron transfer and hydrogen atom donation [50]. Among these, the enol tautomer demonstrates greater thermodynamic stability, primarily due to robust intramolecular hydrogen bonding [51].

Curcumin is also sensitive to photodegradation when exposed to ultraviolet (UV) and visible light, both in solution and in solid-state forms. The degradation rate is significantly accelerated in the presence of light and atmospheric oxygen [47]. It has a high absorbance in the UV-visible range, with peak absorption usually seen between 408 and 430 nm, with polar liquids showing the highest absorption around 420 nm [52]. Experimental findings have shown that curcumin's stability declines rapidly in neutral to alkaline pH conditions, especially between pH 3 and 7, suggesting enhanced decomposition in such environments [53]. Its photoinstability is further exacerbated by self-sensitized photooxidation, as curcumin acts as a singlet oxygen photosensitizer. Therefore, to minimize photodegradation, curcumin should be protected from direct sunlight and oxygen exposure [54].

Moreover, the photochemical behavior and spectral characteristics of curcumin are highly dependent on the nature of the solvent. In biological systems, curcumin's phototoxic potential may be influenced by reactive oxygen species such as singlet oxygen and superoxide, as well as by products generated from photodecomposition processes [55].

3.7. Degradation

Turmeric contains three principal diarylheptanoids: curcumin, demethoxycurcumin (DMC), and bisdemethoxycurcumin (bisDMC). A study investigating the photodegradation quantum yields of curcumin and bisDMC in polar solvents such as acetonitrile and methanol revealed that both compounds exhibited a single exponential decay pattern in media with weak hydrogen bonding interactions [56]. Notably, bisDMC demonstrated a lower quantum yield and underwent faster degradation compared to curcumin under these conditions [57]. Conversely, in solvents exhibiting strong hydrogen bonding capacity, bisDMC displayed slower photodegradation and a higher quantum yield, suggesting that the polarity and hydrogen bonding environment significantly influence the rate of decay of their excited singlet states [58]. In nonpolar solvents, bisDMC decayed more slowly than curcumin via mechanisms such as excited-state intramolecular proton transfer and reketonization; however, negligible deactivation was observed when intermolecular charge or energy transfer occurred in environments with strong hydrogen bonding [59]. Despite its structural differences, bisDMC underwent more extensive photodecomposition under identical conditions than curcumin, indicating that increased photostability in curcumin is not solely attributable to the presence or absence of methoxy groups [56].

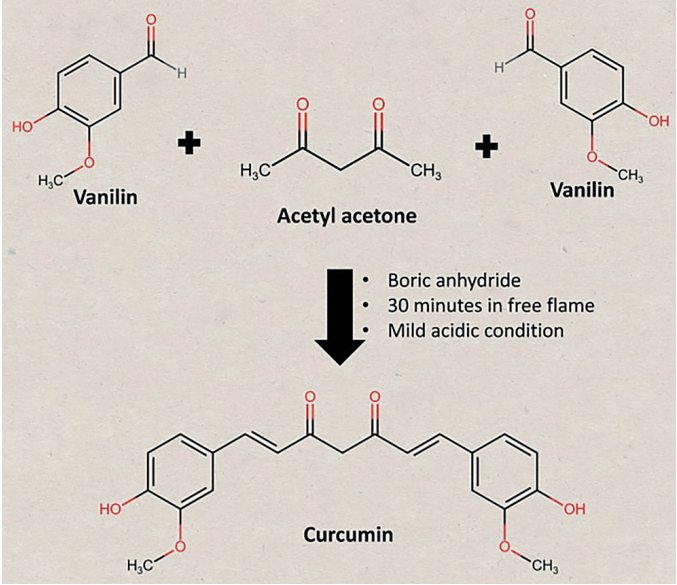

Figure 4. **Synthesis of curcumin**
Рисунок 4. **Синтез куркумина**

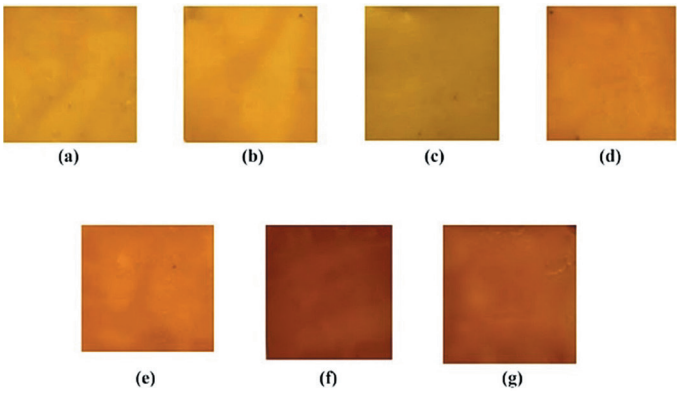

Figure 5. **Color changes of tapioca starch/curcumin films at pH values a 5, b 6, c 7, d 8, e 9, f 10 and g 11**
Рисунок 5. **Изменение цвета пленок из тапиокового крахмала/куркумина при значениях pH: a) 5, b) 6, c) 7, d) 8, e) 9, f) 10 и g) 11**

Curcumin's thermal instability presents additional challenges, especially in culinary applications. Thermal processing, such as roasting and baking, induces various chemical transformations that can reduce its biological efficacy [10,26]. For example, roasting curcumin caused it to degrade significantly; after five minutes, just 30% of the original component was left, and 4-vinyl guaiacol was the predominant breakdown product. Ferulic acid was created quickly in the first degradation phase, then converted more slowly to 4-vinyl guaiacol and finally to volatile phenolic compounds such as isoeugenol, guaiacol, and vanillin, despite the fact that it did not accumulate in significant quantities [60]. Minor traces of vanillin were detected. Interestingly, roasted curcumin applied to RAW264.7 macrophage cells at a concentration of 20 μM did not exhibit cytotoxic effects. Curcumin is highly sensitive to thermal and pH changes, with its dicarbonyl moieties and the central carbon in the heptanoid chain being the most susceptible to degradation [61]. Decomposition involves oxidative cleavage followed by decarboxylation, especially under exposure to heat and oxygen [62]. Experimental data indicate that heating at 180 °C for 50 minutes produced the highest concentration of 4-vinyl guaiacol, which subsequently decreased upon extended roasting due to conversion to diketene derivatives [60]. These findings highlight the critical importance of fine-tuning processing conditions to preserve the functional properties of curcumin and other bioactive plant compounds [63].

3.8. Solubility

The primary cause of curcumin's reduced bioavailability is its water-insoluble nature. Its bioavailability is increased via solid encapsulation and dispersion methods, as well as micro and nano curcumin solutions [16]. Nonetheless, the bioagent has good solubility in organic solvents such as acetone, 2-propanol, ethanol, methanol, dimethoxy sulfoxide (DMSO), and chloroform [28]. The natural substance curcumin may become at least 104 times more soluble in water at pH 5 if a cyclodextrin complex is formed from it [64]. This compound also demonstrates greater hydrolytic stability under alkaline circumstances but produces an increased rate of photodecomposition, relative to curcumin solutions in organic solvents [65]. The degradation rate and stability constant for curcumin complexation are influenced by the cyclodextrin's elasticity, cavity size, and side chain charge [66].

4. Health benefits

Following ingestion, curcumin is predominantly metabolized in the gastrointestinal tract, liver, and colon, with the gut microbiota playing a significant role in its biotransformation [67]. This metabolic process occurs in two distinct phases, both enzymatically driven. In the initial phase, reductase enzymes in intestinal and hepatic cells catalyze the hydrogenation of the heptadiene-3,5-dione moiety, sequentially producing dihydrocurcumin, tetrahydrocurcumin, hexahydrocurcumin, and octahydrocurcumin [36]. The subsequent phase involves conjugation reactions mediated by glucuronidase and sulfotransferase enzymes, which attach glucuronic acid and sulfate groups to the phenolic hydroxyl groups of curcumin and its reduced metabolites. This results in the formation of glucuronide and O-sulfate conjugates, which represent the primary circulating metabolites of curcumin in vivo [68]. A wide array of clinical studies has substantiated curcumin's broad-spectrum bioactivity, including its antimicrobial, antidepressant, anticancer, and antioxidant properties [69].

4.1. Antioxidant properties

Curcumin has been shown to mitigate mitochondrial oxidative stress by enhancing the enzymatic activities of endogenous antioxidants such as glutathione, catalase, and superoxide dismutase [70]. Its molecular structure contains three redox-active sites that can undergo hydrogen atom abstraction and oxidation, resulting in the formation of phenoxy radicals that stabilize its enol form through resonance mechanisms [37]. A daily dose of 645 mg of curcumin over 67 days significantly boosted total antioxidant capacity and decreased malondialdehyde (MDA) levels, indicating reduced lipid peroxidation, according to a meta-analysis of 308 participants, 60 % of whom were female [71].

An in vivo investigation further explored curcumin's hepatoprotective and cardioprotective effects against doxorubicin (DOX), a chemotherapeutic agent known for its adverse hepatic and cardiac effects. In this study, rats were administered a single intraperitoneal dose of DOX (20 mg/kg) to induce toxicity, while curcumin (100 mg/kg orally) was given for ten days before and five days following DOX administration. The protective effects of curcumin were attributed to its anti-inflammatory and antioxidant mechanisms, which include the suppression of lipid peroxidation, downregulation of nuclear factor-kappa B (NF-κB), inhibition of inducible nitric oxide synthase (iNOS) and tumor necrosis factor-alpha (TNF-α), as well as reduction in circulating interferon-gamma (IFN-γ) levels. These findings support the potential role of curcumin as an adjuvant therapy to attenuate DOX-induced hepatotoxicity and cardiotoxicity through antioxidant-based pathways [72].

4.2. Antibacterial properties

The antimicrobial potential of curcumin was first documented by Schraufstatter and colleagues in 1949, marking an early recognition of its bioactive properties [73]. Despite inherent limitations such as low aqueous solubility, poor pharmacokinetics, and limited systemic bioavailability, contemporary studies have consistently highlighted curcumin's potent antibacterial activity [74]. Its antimicrobial mechanisms involve disruption of bacterial cell membranes, interference with intracellular processes through interaction with key proteins and nucleic acids, and inhibition of quorum sensing pathways essential for bacterial communication and virulence [75].

A study conducted by Dizaj et al. [76] investigated the antibacterial efficacy of curcumin nanocrystals against *Porphyromonas gingivalis*, a pathogen isolated from gingival crevicular fluid of Iranian patients experiencing dental implant failure. The research employed the broth microdilution technique to determine the minimum inhibitory concentration (MIC) and utilized the disc diffusion assay to evaluate bacterial susceptibility. Curcumin nanocrystals produced the largest inhibition zone at a concentration of 50 µg/mL. Furthermore, the MIC assay demonstrated bacterial growth inhibition at 6.25 µg/mL, while the minimum bactericidal concentration (MBC) was established at 12.5 µg/mL, confirming the nanoparticles' bactericidal potential against *P. gingivalis* [76].

4.3. Anti-diabetic properties

Research involving diabetic subjects has demonstrated that curcuminoids may positively influence glucose metabolism by enhancing insulin sensitivity and reducing circulating levels of pro-inflammatory cytokines such as leptin, resistin, interleukin (IL)-6, IL-1β, and tumor necrosis factor-α (TNF-α). In addition, curcuminoids have been shown to elevate adiponectin secretion while lowering both insulin and blood glucose levels, thereby contributing to improved glucose homeostasis and glycemic control in diabetes management [77].

In a related preclinical investigation, the synergistic effect of regular physical exercise combined with a curcumin-enriched diet (5 g/kg) was assessed in male Long-Evans Tokushima Fatty Otsuka rats and Long-Evans Tokushima Otsuka (LETO) control rats. The intervention resulted in improved glucose homeostasis, more favorable lipid profiles, body weight reduction, and a marked decrease in endoplasmic reticulum (ER) stress markers as well as inflammatory mediators such as IL-6, TNF-α, and IL-10. Furthermore, cognitive performance assessed via the Morris water maze test showed that curcumin supplementation enhanced escape latency and memory retention, indicating neuroprotective effects [78].

Another experimental study evaluated the inhibitory effects of curcumin on alpha-amylase activity in rats administered doses of 10, 20, 40, and 80 mg/kg over 30 days. Blood glucose levels were monitored every three days, while insulin levels were assessed at the beginning, midpoint, and conclusion of the study. Results indicated that curcumin significantly reduced glucose and insulin concentrations and effectively inhibited alpha-amylase, with an IC_{50} of 51.32 µM and a Ki value of 20.17 µM [79].

Additionally, curcumin has been reported to activate 5′-adenosine monophosphate-activated protein kinase (AMPK), a metabolic regulator that shifts energy metabolism from lipogenesis to fatty acid oxidation, thereby decreasing hepatic glucose production and enhancing glucose uptake in muscle tissue. In gestational diabetic rat models, curcumin administration activated AMPK and modulated hepatic oxidative stress by altering levels of thiobarbituric acid reactive substances (TBARS), superoxide dismutase (SOD), glutathione, and catalase [80].

4.4. Antidepressant properties

Emerging evidence suggests that depression is strongly associated with dysregulation of the brain-gut axis and imbalances in the gut microbiota composition [81]. The integrity of the gut barrier may be compromised by changes in intestinal microbial populations, which could result in increased permeability. This could then impact neurotransmitter signaling and lower levels of brain-derived neurotrophic factor (BDNF), which are thought to be the mechanisms underlying depressed symptoms [82]. Given that the gastrointestinal tract and liver are the main sites of curcumin metabolism, it is proposed that curcumin exerts neuroprotective effects by modulating gut microbiota and reducing intestinal inflammation, thereby influencing brain function through the gut-brain axis [83].

Curcumin's potential efficacy in treating major depressive disorder (MDD) is supported by several biological mechanisms, including enhancement of hippocampal neurogenesis, inhibition of monoamine oxidase (MAO) activity, modulation of key neurotransmitters such as serotonin, dopamine, and norepinephrine, as well as its anti-inflammatory properties [84]. In a 12-week randomized, double-blind, placebo-controlled clinical trial, Kanchanatawan et al. [85] evaluated the adjunctive benefits of curcumin in 65 patients with MDD. Participants were randomly assigned to receive curcumin supplementation or a placebo. Results indicated significant improvements in depressive symptoms, as measured by the Montgomery-Åsberg Depression Rating Scale (MADRS), beginning at week 12 and persisting four weeks post-treatment. Notably, curcumin demonstrated superior efficacy compared to placebo in alleviating symptoms of depression, with statistically significant group differences observed at weeks 12 and 16. Furthermore, the antidepressant effects of curcumin appeared to be more pronounced in male participants.

4.5. Anticancer properties

Conventional therapeutic modalities for cancer, including surgery, chemotherapy, radiotherapy, and immunotherapy, aim to either eradicate malignancies or delay disease progression. However, these approaches often present limitations in efficacy and are frequently accompanied by significant adverse effects [86,87]. Curcumin, a natural polyphenol, has been extensively studied for its anticancer potential due to its ability to modulate multiple intracellular signaling pathways. These include STAT3, NF-κB, early growth response protein 1 (Egr-1), activator protein-1 (AP-1), P53, Wnt/β-catenin, PI3K/Akt, JAK/STAT, and MAPK cascades [88,89].

In an in vitro investigation, Li et al. [90] assessed curcumin's therapeutic potential in colorectal cancer. The results revealed that curcumin selectively inhibited the proliferation of colon cancer cells without cytotoxic effects on normal colonic epithelial cells. It upregulated the pro-apoptotic protein Bax and induced apoptosis through P53-dependent mechanisms. Furthermore, curcumin was shown to impede cell cycle progression at the S phase by suppressing Rb protein phosphorylation, decreasing the synthesis of cell cycle-regulatory proteins, and downregulating E2F family transcription factors.

Similarly, Kamalabadi et al. [91] evaluated the anticancer effects of curcumin on breast cancer using three-dimensional (3D) multicellular spheroids, a model that better preserves the physiological properties of tumors compared to traditional two-dimensional (2D) cultures. Their findings indicated that curcumin exerted cytotoxic effects on MCF-3 breast cancer cells in both 2D and 3D systems in a dose- and time-dependent manner. Despite curcumin's low bioavailability, these results highlight its significant antiproliferative activity in in vitro tumor models.

5. Functional edible films: A new concept in food packaging

Food packaging serves a number of purposes, such as informational, marketing, and confinement [92]. Traditional food packaging serves the primary purposes of keeping food isolated from its surroundings, minimizing changes to the food, ensuring greater stability, reducing interaction with spoilage factors (such as light, oxygen, water vapor, microorganisms, etc.), and ultimately extending the food's shelf life while in storage [93].

Edible film is a type of primary packaging that is applied to food and is formed of edible ingredients that have been solidly laminated [94]. Edible films, which have no nutritional, functional, or sensory value, have been created for uses such as wrapping food items and serving as a protective covering [95]. On the other hand, films with these qualities might be preferred for uses like the principal packaging of breakfast cereals or the packing of items that are ready to eat, such as sushi, sandwiches, and frozen pizza [96].

The primary biopolymers utilized in the creation of edible films include proteins, polysaccharides, lipids, and mixtures of these substances [97]. Proteins and polysaccharides have drawn increased attention due to their unique qualities, which include their relative abundance, nutritional value, and capacity to produce good film layers [98]. Edible film coatings are often made from polysaccharides such as locust bean gum, agar, xanthan, carrageenan, guar, pectin, and alginate [99]. The most researched proteins for the creation of edible film coatings for foods are zein, gelatin, casein, whey protein, and soy protein [100]. Although the majority of lipid compounds cannot form film layers on their own, some oils and waxes, such as palm oil and carnauba wax, can be combined with hydrocolloids to generate composite layers that have better moisture resistance since lipids are hydrophobic [101].

In addition to the sustainability that biopolymer films are projected to provide, edible functional films with bioactive qualities are made for consumers who are concerned about health and nutrition (Figure 6). In addition to being edible, this packaging contains bioactive ingredients like flavonoids, marine oils, probiotics, and prebiotics that may improve consumers' health [7]. One novel technique that is currently gaining traction is edible functional films, which are a creative take on the idea of functional meals in relation to a sustainable approach [102].

Functional edible films have garnered attention for their ability to facilitate the controlled delivery of bioactive compounds through the human gastrointestinal (GI) tract, particularly targeting the intestinal region where these substances can adhere to the epithelial mucosa and subsequently enter the lymphatic circulation [103]. To achieve this, it is essential that the encapsulated bioactives remain stable and are not prematurely degraded or released in the upper GI tract, where absorption is typically inefficient or negligible [104]. These films must therefore be engineered to resist variations in pH and enzymatic digestion throughout the GI system.

The effectiveness of these films is closely linked to the physicochemical interactions between the biopolymer matrix and the embedded bioactive agents. The specific type of polymer utilized in the formulation plays a critical role in determining the release kinetics and overall concentration of the bioactive compounds in the target environment. Thus, the release profile of the functional "payload" must be precisely characterized and optimized [105].

In scholarly literature, the term "bioactive film" is predominantly used to describe edible films that incorporate health-promoting bioactive constituents [7]. However, in some contexts, the term has also been applied to films designed to impart beneficial properties to food products, such as antioxidant or antimicrobial effects [106–108]. In light of this ambiguity, it is proposed that the terminology "functional edible films" be adopted to more accurately describe edible films specifically developed to enhance human health outcomes.

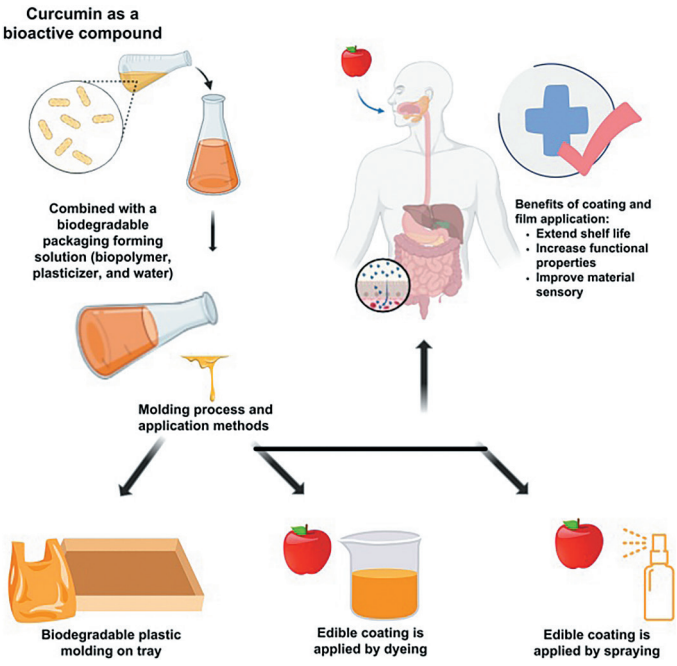

Figure 6. **An overview of functional edible films and their actions**
Рисунок 6. **Обзор функциональных съедобных пленок и их свойств**

6. Curcumin: A bioactive molecule with potential for edible bioactive film production

Bioactive compounds, a class of phytochemicals extractable from food or food-derived waste, are recognized for their capacity to support health and influence metabolic pathways [109]. Among them, curcumin, a principal component derived from the rhizome of *Curcuma longa* of the Zingiberaceae family, exhibits a symmetrical molecular structure characterized by a β-diketone enol form and two ortho-methoxyphenolic rings joined by a heptacarbon chain [37,110]. Curcumin is widely acknowledged for its therapeutic potential, notably in the management of conditions such as neurodegenerative diseases, diabetes, metabolic syndrome, cancer, cardiovascular disorders, and arthritis, due to its antioxidant, anti-inflammatory, and antimicrobial properties [111].

The phenolic hydroxyl groups within curcumin's molecular framework play a critical role in neutralizing reactive oxygen and nitrogen species, thus contributing significantly to its antioxidative activity [112]. Additionally, curcumin enhances redox homeostasis by modulating the nuclear factor erythroid 2-related factor 2 (Nrf2), which in turn activates antioxidant response elements and provides cellular defense against oxidative insults, particularly in age-related diseases [113].

In terms of antimicrobial applications, curcumin promotes wound healing, especially among elderly populations, due to its antibacterial properties [114]. It also displays antiviral activity by inhibiting inosine monophosphate dehydrogenase, thereby disrupting nucleotide synthesis crucial to DNA and RNA virus replication [115]. Furthermore, its phenolic constituents regulate inflammation by suppressing transcription factors such as activator protein-1 (AP-1) and nuclear factor kappa B (NF-κB), which are integral to the inflammatory response [116].

The World Health Organization has reported that chronic illnesses, including diabetes, cancer, and cardiovascular diseases, account for approximately 71 % of global mortality [117]. In this context, curcuminoids exert cardioprotective effects through anti-inflammatory mechanisms, oxidative stress modulation, and inhibition of apoptosis [118]. These compounds also attenuate joint inflammation in arthritis by targeting key signaling molecules such as kinases [119], and their anti-obesity potential is mediated through regulation of oxidative balance and anti-inflammatory enzyme expression [120]. A clinical study demonstrated that six weeks of supplementation with 1 g/day of curcumin in its phospholipidated form significantly improved zinc-to-copper ratios and plasma zinc levels in patients with metabolic syndrome being two indicators of enhanced antioxidant defense [121].

Curcumin's antidiabetic properties have been extensively studied, with mechanisms linked to the regulation of glucose metabolism and insulin

secretion [122]. In diabetic rats, administration of curcumin-enriched yogurt improved lipid profiles (triacylglycerol and total cholesterol reduced by 61 % and 21 %, respectively) and carbohydrate metabolism biomarkers (63 % reduction), while increasing paraoxonase activity by 31 % compared to controls [123]. Similarly, a 12-week trial involving 60 women with polycystic ovary syndrome revealed that 500 mg/day of curcumin improved insulin sensitivity, reduced body weight, serum lipid levels (triglycerides decreased from 163.6 ± 44.8 to 154.0 ± 29.4 mg/dL), and glycemic markers (fasting insulin decreased from 111.3 ± 3.6 to 10.1 ± 3.2 μIU/mL) [124].

In oncology, curcumin impedes cancer progression through anti-angiogenic and anti-lymphangiogenic effects, regulation of tumor suppressor proteins (e. g., p53), and inhibition of cancer cell proliferation, apoptosis, and invasion [125]. Furthermore, curcuminoids are especially useful because of their capacity to regulate neuroinflammation, oxidative stress, neurotransmitter synthesis (including dopamine and serotonin), and mitochondrial stability. This is especially important given the reciprocal relationship between mental illness and chronic diseases, where one may raise the risk of the other [113,126].

Although curcumin has gained considerable attention as a bioactive food ingredient or nutraceutical, its clinical utility is hampered by poor water solubility, chemical instability, and low systemic bioavailability, which contribute to its suboptimal pharmacokinetic profile [41]. Effective therapeutic outcomes often necessitate high dosages, which is a limitation when using turmeric extracts in food systems [9]. This limited bioavailability is attributed to several physicochemical and physiological factors, such as low aqueous solubility, limited permeability in the gastrointestinal tract, instability at physiological pH, and extensive first-pass metabolism in both the liver and intestines [127].

7. Encapsulation of curcumin for application as a bioactive agent

The limitations associated with curcumin utilization, such as its low solubility and bioavailability, may be effectively addressed through encapsulation within food-grade biopolymers or colloidal delivery systems [12]. Encapsulation techniques enhance the physicochemical stability of curcumin and protect it from enzymatic degradation, hydrolysis, and conjugation-based inactivation, thereby facilitating improved gastrointestinal absorption [128]. Various delivery platforms have been developed for curcumin, including micelles, emulsions, nanoemulsions, liposomes, microgels, biopolymeric nanoparticles, and molecular complexes (Figure 7).

In an investigation by Zheng et al. [129], the type of curcumin delivery system was found to significantly influence its gastrointestinal bioaccessibility. Nanocrystals had the lowest bioaccessibility among the investigated systems (nanoemulsions, soy milk, and nanocrystals) because of their restricted micelle-mediated solubilization. In contrast, Peng et al. [130] demonstrated that the encapsulation of curcumin in sophorolipid-coated nanoparticles led to a 2.7–3.6-fold increase in bioavailability in both in vitro and in vivo settings compared to unencapsulated curcumin.

Liu et al. [131] reported that curcumin encapsulated within amphiphilic starch-based micelles exhibited a controlled release profile, with approximately 55 % release sustained over a 7-hour intestinal simulation. Furthermore, Gómez-Mascaraque et al. [132] enhanced curcumin bioaccessibility by 1.7-fold using hybrid nanostructures composed of phosphatidylcholine liposomes embedded in an electrospray wood-polymer composite matrix.

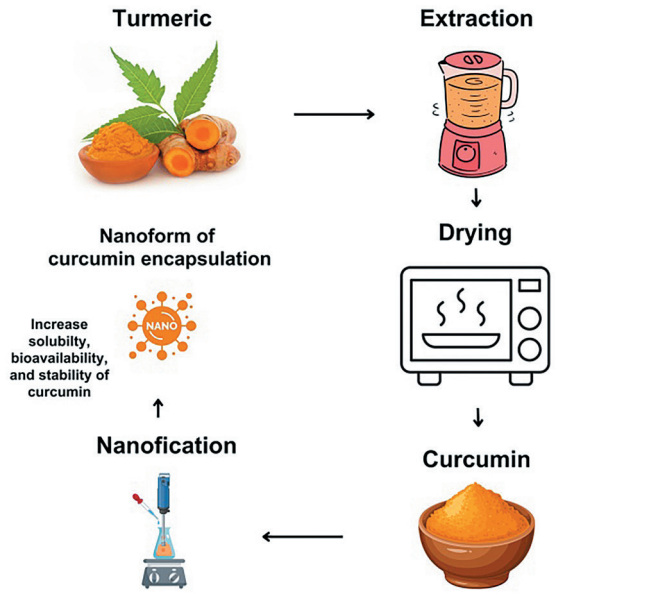

Figure 7. **Overview of curcumin micro/nanoencapsulation**
Рисунок 7. **Обзор микро-/нано-инкапсуляции куркумина**

Emulsion-based systems have emerged as efficient carriers for curcumin due to their ability to solubilize lipophilic compounds and improve both chemical stability and absorption [133]. Aditya et al. [134] found that curcumin encapsulated in a water-in-oil-in-water double emulsion exhibited significantly greater bioaccessibility (72 %) compared to its free form (16 %). Similarly, nanoemulsions fabricated via conventional oil-loading, heat-driven, and pH-driven approaches yielded comparable bioaccessibility values ranging from 74 % to 79 %, approximately 7–8 times higher than curcumin in aqueous solution [129]. These findings suggest that lipid-based encapsulation may substantially enhance gastrointestinal uptake of curcumin.

The composition of the carrier lipid also plays a pivotal role in determining curcumin's bioaccessibility. Ahmed et al. [135] observed that emulsions formulated with short-chain triacylglycerols yielded bioaccessibility as low as 1 %, whereas those incorporating medium- and long-chain triglycerides resulted in significantly higher bioaccessibility values of 20 % and 40 %, respectively. Shah et al. [136] further corroborated these results, reporting bioaccessibility of 32 % and 65 % for curcumin-loaded nanoemulsions containing medium- and long-chain triacylglycerols, respectively. Higher total lipid content may promote the formation of mixed micelles capable of solubilizing curcumin; however, excessive lipid quantities could hinder micelle formation if digestion is incomplete, thus limiting the release of curcumin from lipid droplets [137].

An alternative encapsulation approach involves the use of pH-shift-induced colloidal particles, leveraging curcumin's solubility changes based on its pKa. At pH levels ⩾ 12, curcumin becomes protonated and water-soluble, whereas it deprotonates and becomes poorly soluble below pH 8.0. This property allows its incorporation into hydrophobic colloidal interiors [16]. Pan et al. [138] employed this method to encapsulate curcumin in casein-based nanoparticles, which demonstrated enhanced antiproliferative efficacy against pancreatic (BxPC3) and colorectal (HCT-116) cancer cells.

Encapsulation technologies thus represent a promising strategy for improving the functionality of curcumin within edible film matrices intended for food applications. These systems enhance curcumin's protection, stability, and bioaccessibility, thereby maximizing its health-promoting potential [7]. Each encapsulation method offers specific advantages and limitations, and the choice of system must be tailored to the intended food application and target bioactive compounds. As such, encapsulation may serve as a viable means to improve the oral bioavailability of curcumin and similar nutraceuticals when incorporated into functional food products.

8. Functional packaging containing curcumin

The incorporation of curcumin as a bioactive component in functional edible films and coatings has garnered increasing attention due to its promising health benefits (Figure 8). Extensive in vitro investigations have revealed that curcumin enhances the antioxidant properties of edible film matrices. For instance, Roy and Rhim [139] reported that integrating 1.5 % (w/w) curcumin into poly(lactic acid)-based films significantly increased antioxidant activity, as determined by DPPH and ABTS assays, from 1.8 % and 3.1 % to 76.6 % and 94.7 %, respectively. Similarly, Xiao et al. [140] demonstrated improvements in antioxidant capacity by approximately 25–35 % and 10–20 % in films composed of cellulose nanocrystals and soy protein isolate using DPPH and ABTS methods. Roy and Rhim et al. [141] also showed that curcumin (1 % w/w) in zinc oxide–carboxymethylcellulose composite films markedly enhanced antioxidant activity to 40.2 % and 92.5 % via DPPH and ABTS assays, respectively. These findings serve as preliminary evidence of curcumin's potential to confer health-promoting properties in bioactive food films.

In addition to antioxidant activity, curcumin-containing biopolymeric films have demonstrated antimicrobial efficacy in vitro [142]. Rostami and Esfahani [143] showed that nanocomposite films incorporating *Melissa officinalis* seed gum, curcumin, and montmorillonite exhibited antibacterial activity against *Bacillus subtilis*, *Bacillus cereus*, and *Escherichia coli*. Taghinia et al. [144] also reported that edible films prepared using *Lallemantia iberica* seed mucilage and curcumin inhibited the growth of *Penicillium expansum*, *B. cereus*, *B. subtilis*, and *E. coli*. Furthermore, Manna et al. [145] demonstrated broad-spectrum antimicrobial activity of curcumin-loaded carboxymethylated guar gum films against both Gram-positive and Gram-negative bacteria. Conversely, Musso et al. [146] found that curcumin at 0.02 % (w/v) in gelatin-based films showed no significant antimicrobial effects against *B. cereus*, *Staphylococcus aureus*, *Salmonella enteritidis*, or *E. coli*.

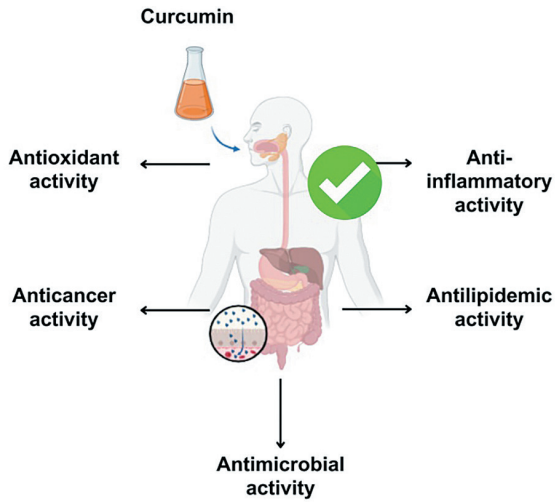

Figure 8. **An overview of the possible beneficial health effects of edible bioactive films containing curcumin**
Рисунок 8. **Обзор возможных полезных свойств съедобных биоактивных пленок, содержащих куркумин**

Despite its bioactive potential, curcumin's clinical efficacy is limited by several physicochemical and biological barriers. The compound suffers from poor water solubility, chemical instability, and rapid metabolism into inactive derivatives, which collectively result in low bioavailability after ingestion [147]. While soluble in lipid environments, curcumin is virtually insoluble in water under acidic or neutral pH at ambient temperature and is prone to rapid degradation in alkaline conditions [12]. Its strong affinity for gastrointestinal mucus further impedes epithelial uptake and increases susceptibility to oxidative and autooxidation degradation [148].

Curcumin-loaded edible films, especially those made with surfactants or emulsifying polymers, have demonstrated the ability to improve their solubility and controlled release in alkaline settings in order to overcome these restrictions [149]. Increasing the concentration of these polymers in aqueous solutions facilitates curcumin solubilization, improving its transport across the intestinal epithelium while minimizing degradation during gastrointestinal transit [66].

The encapsulation of curcumin in edible film matrices offers a viable strategy to mitigate its inherent drawbacks and enhance its in vivo efficacy. Gunathilake et al. [150] found that a composite film made from poly(lactic acid), sodium carboxymethylcellulose, and curcumin facilitated a more efficient release under intestinal pH conditions. In phosphate-buffered saline, carboxymethylcellulose, which becomes soluble and swells in neutral to alkaline media, forms emulsions with curcumin that potentially enhance its permeation through the mucus barrier and absorption by epithelial cells. Conversely, Zhang et al. [151] showed that incorporating curcumin into whey protein microgels slowed its release under simulated gastrointestinal conditions, suggesting that while some biopolymers may offer sustained release, they do not necessarily enhance bioavailability.

Applications of edible bioactive films incorporating curcumin have also been explored in various food matrices. For example, Ghosh et al. [152] demonstrated that nanofiber/chitosan-based coatings enriched with curcumin reduced weight loss, texture degradation, respiration rate, and microbial growth in kiwifruit during storage. Shen et al. [153] reported that chitosan-curcumin nanoparticle coatings effectively suppressed lipid oxidation in pork. Similarly, Bojorges et al. [154] found that edible films based on curcumin and alginate were effective in reducing lipid oxidation in chicken, beef, and pork. Nevertheless, these studies have yet to evaluate the sensory attributes or bioactive efficacy of such films in consumer contexts.

Overall, the biological activity of curcumin supports its role as a promising natural compound for the formulation of functional edible films in food systems. Despite encouraging in vitro results, its application as a delivery system in food matrices remains underexplored, particularly regarding its in vivo bioavailability and sensory impact. Future research should prioritize evaluating the release kinetics, functional efficacy, and consumer acceptance of curcumin-containing bioactive films across various food products [155].

9. Commercial prospects of curcumin in food packaging

Curcumin, a naturally occurring polyphenolic compound, has attracted significant interest in recent years owing to its diverse applications and multifunctional properties. Turmeric, the main source of curcumin, has long been used in food and traditional medicine but is now a highly prized commodity, especially in the pharmaceutical industry [10]. This shift has notably influenced the global curcumin market, which was valued at USD52.45 million in 2017 and is projected to reach USD104.19 million by 2025, reflecting a compound annual growth rate (CAGR) of 8.9% [24]. While curcumin continues to be widely used as a functional additive and natural colorant, the pharmaceutical industry remains the primary consumer, followed by the food and beverage sector [8]. Nonetheless, its application in food packaging materials has yet to be realized at a commercial scale.

A notable initiative addressing this gap is the CurCol project, funded under Interreg Northwest Europe, which aims to utilize curcumin as a natural and biodegradable alternative to synthetic dyes for coloring bioplastics and paper packaging [156]. Led by the Avans Foundation and supported by multiple European partners, the project received €1.57 million in funding from the European Union, out of a total research budget of €2.61 million. The project explores the potential of curcumin-based yellow dyes, along with their capacity to produce various hues such as red and blue, while focusing on enhancing the pigment's stability during processing. As a result, commercial interest in curcumin continues to grow, and its future use as a functional additive in food packaging materials appears increasingly likely based on evolving market dynamics.

10. Future research perspectives

The potent antioxidant and halochromic properties of curcumin have catalyzed interest in its use in active and intelligent food packaging applications. Despite these promising attributes, several limitations must be addressed before curcumin-based films can be widely adopted. A key challenge is curcumin's poor water solubility, which diminishes its functional efficacy in aqueous environments, such as microbial cells and food matrices that are predominantly water-based [21]. This limitation is a principal factor contributing to the suboptimal antibacterial performance observed in some curcumin-infused films [141]. However, this drawback may be overcome by incorporating curcumin into emulsions before its integration into film-forming systems [114].

The use of emulsification techniques has demonstrated encouraging outcomes for integrating hydrophobic active agents into hydrophilic biopolymer matrices, thereby improving their dispersibility and functional performance [157]. Another obstacle lies in the scalability of curcumin-based materials, as they are not always compatible with standard polymer processing techniques used in industrial production [64]. Curcumin is thermally sensitive, and its molecular structure can degrade at elevated temperatures, thereby restricting its applicability in high-temperature processing environments [158]. Addressing challenges such as the thermal and color stability of pH-responsive films is crucial for the successful processing and commercialization of curcumin-based packaging materials [159].

Future research efforts should prioritize the development of advanced processing methods to improve dye solubility, enhance thermal and color stability, and optimize the manufacturing of active and intelligent packaging films. Furthermore, even at gram-level concentrations, curcumin is safe for human consumption; nonetheless, its use in edible food coatings is still unexplored and needs more research.

11. Conclusion

Curcumin, the primary bioactive compound in *Curcuma longa*, exhibits strong potential as an active ingredient in edible food packaging due to its antioxidant, anti-inflammatory, antimicrobial, and anticancer properties. Despite its therapeutic promise, curcumin's poor water solubility, instability under light and heat, and low bioavailability limit its effectiveness in food and biomedical applications. Advances in encapsulation and nano-delivery systems have shown promise in overcoming these limitations, enhancing its functionality and potential for health-promoting applications.

Incorporating curcumin into functional edible films not only supports food preservation and safety but also contributes to environmental sustainability by offering alternatives to plastic-based packaging. These films can also serve as smart packaging indicators due to curcumin's sensitivity to pH and environmental conditions. However, further research is needed to improve its bioavailability in real food systems, ensure consumer acceptance, and address challenges in industrial scalability for commercial use.

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