Research Progress on Active Components, Efficacy and Delivery Systems of Cinnamon

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Abstract: Cinnamomum cassia Presl (Cinnamon), formerly known as Cinnamomum burmannii and Cinnamomum japonicum, is an evergreen tree of the genus Cinnamomum in the Lauraceae family, widely distributed in southern China and Southeast Asia. Cinnamon is not only an important spice and medicinal material but also rich in various physiologically active ingredients, with a wide range of pharmacological effects, including antioxidant, anti - inflammatory, hypoglycemic, and antibacterial effects. Its main active ingredients include cinnamaldehyde, cinnamic acid, coumarin, etc. These ingredients have important applications in both traditional Chinese medicine and modern medicine. Delivery systems such as microcapsules, nano - emulsions, and micelles are used to improve the stability and bioavailability of cinnamon's active ingredients and are widely used in fields such as food and medicine. Despite significant progress, the stability, release mechanism, and large - scale application of cinnamon's active ingredients still require further research. Future research directions include optimizing the delivery system, conducting in - depth exploration of the mechanism of action, and developing new delivery systems in combination with modern biotechnology to promote the comprehensive development and utilization of cinnamon resources.

Keywords: Cinnamon; Active Components; Pharmacological Effects; Antibacterial; Delivery Systems; Bioavailability; Stability; Modern Biotechnology

1. Active Components of Cinnamon and Their Effects

1.1 Volatile Oil

As the main active component of cinnamon (Cinnamomum cassia Presl), cinnamon volatile oil has attracted much attention in recent years due to its wide range of biological activities. An et al. [1] analyzed it through techniques such as gas chromatography - mass spectrometry (GC - MS). Its chemical composition is complex, mainly including trans - cinnamaldehyde, α - copaene, β - cadinene, etc. Among them, trans - cinnamaldehyde is the core component, with a content of up to 62.16% [2]. Studies have shown that there are significant differences in the components of cinnamon volatile oil from different producing areas and growth environments. New components such as β - phellandrene and fenchone were first identified in cinnamon produced in Yulin, Guangxi [3]. There are also differences in the oil yield and quality among different cultivation areas in Guangxi. For example, the volatile oil content of the Gui 26# sample reaches 1.82%, and its quality is the best [4]. In addition, the extraction process and growth years have a significant impact on the active components of volatile oils. The optimized extraction process using steam distillation can increase the oil yield to 6.41% [3].

1.2 Diterpenoids

The diterpenoid compounds in Cinnamon mainly belong to the Ryanodane type, with complex highly oxygenated polycyclic structures. Zhao et al. [5] confirmed through X-ray crystallography and nuclear magnetic resonance technology that Ryanodane components such as cinnzeylanine and anhydrocinnzeylanine were isolated for the first time from domestic Cinnamon. Their structures contain an eight-membered ring and multiple chiral centers.

1.3 Polyphenols

Cinnamon polyphenols are important water-soluble active components in cinnamon. In recent years, they have become a research hotspot due to their wide range of pharmacological effects. Their chemical components mainly include flavonoids, proanthocyanidins (type A, type B), methylhydroxychalcone, epigallocatechin gallate (EGCG), condensed tannins, and ferulic acid. Among them, proanthocyanidins are considered the key components for anti - diabetes [6]. The extraction process of polyphenols has been continuously optimized. The combination of water extraction method and enzyme catalysis technology can increase the extraction rate to 15.49 mg/g, which is 20.92% higher than the traditional method [7].

1.4 Other Components

Lignans are one of the important active components in cinnamon, with complex polycyclic structures and diverse biological activities. Research has found that multiple lignin compounds, (7S,8R)-dihydrodehydrodiconiferyl alcohol glycoside, and various lyoniresinol derivatives can be isolated from the ethyl acetate fractions of cinnamon bark and leaves. These compounds were all isolated from cinnamon for the first time [8]. The aromatic compounds in cinnamon mainly include coumarin, cinnamic acid, and their derivatives. Cinnamon polysaccharides have been a hot topic in recent research, especially for their prominent hypoglycemic mechanism. By optimizing the extraction process using the water extraction and alcohol precipitation method (temperature 90°C, liquid-to-material ratio 20:1), the yield of polysaccharides can reach 3.22%. The relative molecular mass of the purified polysaccharides is 1.95×10^6 Da, with a mixed α and β configuration [9].

2. Biological Activities of Cinnamon and Its Active Components

2.1 Antioxidant Effect

Active components such as volatile oils and polyphenols in cinnamon have antioxidant effects. The strong reducibility of polyphenols enables them to effectively scavenge free radicals and reduce oxidative stress markers. The IC50 value of DPPH free radical scavenging ability is as low as 4.0 μg/mL, and the inhibition rate of β - carotene bleaching reaches 68.6% (at a concentration of 1.6 mg/mL). Its antioxidant capacity is comparable to that of vitamin C [7]. Hwan et al. [10] used literature review and network pharmacology analysis and found that active components such as cinnamaldehyde and cinnamic acid can regulate oxidative stress responses, inhibit inflammatory responses, and promote the repair of gastric mucosa, significantly alleviating gastric damage caused by ethanol. The antioxidant capacity of cinnamon flavonoids has been outstanding in multiple experiments. Zhao [11] identified through the HPLC - DPPH combined technology that the chemical components of cinnamon flavonoids, procyanidin B2, gallic acid, and epicatechin, have strong antioxidant activities. Ku et al. [12] found that in terms of scavenging superoxide anion radicals and inhibiting lipid peroxidation, their effects are better than those of food - grade antioxidants Vc and PG.

2.2 Anti - inflammatory Effect

The active components such as volatile oils and polyphenols in cinnamon have anti - inflammatory effects. Zhao et al. [5] found in their research that ryanodane - type diterpenes, such as the Cinncassiols series of components, showed significant anti - complement activity and may inhibit the inflammatory response by regulating the immune pathway.Hu [7] found in his research that cinnamon polyphenols can relieve the inflammatory response in rats with rheumatoid arthritis models by inhibiting pro-inflammatory factors (TNF-α, IL-6) and the JNK/p38 signaling pathway, with a maximum inhibition rate of 38.92%. Ku et al. [12] found in their research that the content of procyanidin C1 in cinnamon is as high as 5,384.02 μg/g, which can inhibit allergic reactions by regulating the balance of Th1/Th2 cells.

2.3 Antibacterial Effect

The main active substances with antibacterial effects in cinnamon are volatile oils. Zhang et al. [3] proved through their research on volatile oils that they have inhibitory effects on 8 common pathogenic bacteria (such as Escherichia coli and Staphylococcus aureus) and 6 drug-resistant bacteria. The minimum inhibitory concentration (MIC) and minimum bactericidal concentration (MBC) are significantly effective, and the antibacterial effect of 15-year-old sparsely planted cinnamon is particularly prominent. Meanwhile, the research by Yan et al. [13] demonstrated that cinnamaldehyde, o-methoxycinnamaldehyde, cinnamyl acetate, and benzaldehyde all have a certain degree of antibacterial activity. They induce oxidative damage to microorganisms, disrupt the integrity of cell membranes, and then induce cell death.

2.4 Other Effects

In addition to the above main effects, the active substances in cinnamon also have anti-cancer and anti-tumor effects and are used in the treatment of dysmenorrhea, diabetes, and Alzheimer's disease. Diterpenoids exert anti-cancer activity by targeting and regulating tumor-related genes. Certain diterpene components inhibit tumor invasion by upregulating the expression of apoptosis-related proteins (such as Caspase-3 and AIF) in breast cancer cells MDA-MB-231 [5]. Yan et al. [13] proved through research that by upregulating the intracellular reactive oxygen species (ROS) level and the expression of apoptosis-related proteins Caspase-3 and AIF, the proliferation, migration, and invasion of MDA-MB-231 breast cancer cells were significantly inhibited, the mitochondrial membrane potential was induced to decrease, and cell apoptosis was promoted ($P < 0.01$).Bao et al. [2] proposed that cinnamaldehyde and cinnamon volatile oil could significantly inhibit ADP-induced platelet aggregation, with inhibition rates reaching 82.5% and 76.6% respectively, suggesting that cinnamaldehyde is the key component for activating the blood to unblock meridians. Pérez et al. [14] found through animal experiments that cinnamaldehyde could reduce the Glu level, activate insulin receptor kinase to improve Glu absorption, and increase insulin to raise the insulin level, and regulate glucose transporters in adipose, liver, and muscle tissues of alloxan-induced diabetic rats, and it was used as an adjuvant for controlling type 2 diabetes. In addition, Kim et al. found in their research [15] that cinnamic acid in cinnamon could also stimulate growth factors related to hair follicle differentiation by activating the Wnt/β-catenin signaling pathway, promote the activation and differentiation of hair follicle stem cells, and then promote hair growth. Li et al. [16] found through in vitro and animal experiments that cinnamon has potential therapeutic effects on neurodegenerative diseases such as Alzheimer's disease (AD) and Parkinson's disease. Flavanols, proanthocyanidins, and cinnamaldehyde can stimulate the BDNF/TrkB pathway, enhance the ability to resist oxidative stress, improve the memory of AD model mice, and alleviate the symptoms of AD.

3. Delivery Systems

The stability of the active components of cinnamon is poor, and they are prone to degradation under the influence of various physicochemical factors such as oxygen, light, temperature, and pH, which limits their application scope. In the future, with the in - depth research on delivery systems, the application fields of the active components of cinnamon will be further expanded, laying a foundation for the comprehensive utilization of cinnamon and the development of high - value - added products.

In order to improve the stability and bioavailability of the active components of cinnamon, researchers have developed a variety of delivery systems. Delivery systems such as emulsions, microemulsions, nanoemulsions, Pickering emulsions, and microcapsules have been used to encapsulate cinnamon essential oil to improve its water solubility and stability.

3.1 Cinnamon Essential Oil Pickering Emulsion

Cinnamon essential oil Pickering emulsion is a delivery system based on solid particle stabilization technology. Its core mechanism is to use nano - or micro - sized solid particles (such as modified starch, protein complexes, inorganic clay, etc.) to form a physical barrier at the oil - water interface, replacing traditional surfactants, thereby achieving efficient encapsulation and sustained release of cinnamon essential oil. The preparation of this type of emulsion is usually completed through high - speed homogenization or ultrasonic dispersion technology. The wettability of the particles (contact angle close to 90°) and the interfacial adsorption capacity are the keys to its stability [17]. In addition, research from Tianjin University of Science and Technology shows that the Pickering emulsion stabilized by TEMPO - oxidized bacterial cellulose (TOBC) can enhance the elongation at break and ultraviolet - blocking ability of the gelatin film while retaining the antioxidant activity of cinnamon essential oil [17]. When used for bacteriostasis, it can enhance the antibacterial activity of cinnamon oil, achieving better results and exerting a long - term bacteriostatic effect. In terms of food preservation, cinnamon essential oil nano - emulsion still has good stability under different concentrations of ascorbic acid. When used in combination with ascorbic acid, it can delay the decline of total phenol and ascorbic acid content in apple juice and effectively control the browning of apple juice to a certain extent. The coating of cinnamon essential oil Pickering emulsion can also control the enzymatic browning of mangoes and delay the decline of mango hardness [18].

3.2 Microemulsion

The microemulsion technology in the cinnamon delivery system is a strategy to improve the solubility and bioavailability of active components in cinnamon (such as cinnamaldehyde) by constructing a thermodynamically stable oil - water - surfactant system. This system uses cinnamon essential oil as the oil phase. By adding emulsifiers such as Tween - 80 and co - emulsifiers such as ethanol and propionic acid, a nano - scale microemulsion region (with a particle size usually less than 100 nm) is formed, thereby achieving efficient encapsulation and sustained release of active ingredients [19]. Research shows that the formula of cinnamon essential oil - ethanol - Tween - 80 with a mass ratio of 1:3:6 can significantly enhance the antibacterial effect against Botrytis cinerea. Its minimum fungicidal concentration (MFC) is 250 μL/L, and the control rate of apple gray mold reaches 100% after combined use with chitosan [20]. In addition, the self - microemulsion system (such as the cinnamaldehyde - loaded self - microemulsion in the patented technology) can rapidly disperse at room temperature to form a stable microemulsion by optimizing the ratio of the oil phase (medium - chain triglycerides) to the emulsifier (polyoxyethylene castor oil). The drug - loading capacity is as high as 5.5%, and it shows a synergistic therapeutic effect on liver fibrosis and steatohepatitis. Microemulsions have high stability, high drug-loading capacity, and good dispersibility. They can effectively protect lipophilic components such as cinnamaldehyde from oxidative degradation and prolong the action time through a sustained-release mechanism. Their preparation process is relatively simple, and industrial production can be achieved without complex equipment [19]

3.3 Nanoemulsion

The nanoemulsion of the cinnamon delivery system Cinnamon Essential Oil Nanoemulsion (CEON) is a delivery system constructed based on nanoemulsification technology. It forms a stable colloidal dispersion system with a particle size of less than 200 nm (usually 10 - 150 nm) by dispersing cinnamon essential oil (the main active ingredient is cinnamaldehyde) in an oil - water - surfactant system [21]. Its preparation process mostly uses the high - pressure homogenization method or the ultrasonic method. Non - ionic surfactants (such as Tween - 80, polyoxyethylene castor oil) and co - emulsifiers (such as ethanol, glycerol) are used to optimize the phase ratio to form an O/W structure [22], which significantly improves the stability, encapsulation efficiency and antibacterial effect of the active ingredients of cinnamon. Yuan et al. [23] prepared a cinnamaldehyde nanofiber membrane through coaxial electrospinning technology, which can achieve an encapsulation efficiency of 95.2% and a stability of 82.5%. The in vitro release amount reaches 57.9% - 89.1% within 24 hours, and the release rate can be regulated by the shell thickness and the content of porogen. In addition, Mai et al. [24] studied a multifunctional nano - system combining chitosan - tannic acid - lysozyme nanoparticles (CS - TA - L NPs) with cinnamaldehyde. Under the trigger of near - infrared light, the precise release of antibacterial components can be achieved, and it has been successfully used for the healing of infected wounds in vivo.

3.4 Microcapsules

The microcapsules of the cinnamon delivery system are micro - carriers formed by encapsulating the active components of cinnamon (such as cinnamaldehyde) in polymer materials (such as chitosan, gum arabic, modified starch, etc.) through physical or chemical methods. Their particle size is usually 1 - 1000 μm. The preparation techniques mainly include spray drying, complex coacervation, layer-by-layer self-assembly, and freeze drying. Tan et al. [25] used the spray drying method to encapsulate cinnamon essential oil with wall materials (such as a mixed solution of gum arabic and maltodextrin). By optimizing the ratio of wall materials (such as a 1:1 mixture of gum arabic and maltodextrin), a 50% retention rate of cinnamaldehyde can be achieved, and spherical particles are formed, significantly improving the thermal stability. The layer-by-layer self-assembly technique constructs a multi-layer microcapsule structure by alternately adsorbing polyelectrolytes with opposite charges (such as chitosan and sodium lignosulfonate). Its encapsulation efficiency can reach 68% - 72%, and the release rate can be controlled by adjusting the pH or ionic strength. In addition, the freeze drying method combines modified porous starch and xanthan gum to simultaneously encapsulate cinnamon essential oil and sodium metabisulfite, achieving a synergistic antibacterial effect. The microcapsules reduce the volatilization and oxidative degradation of cinnamaldehyde through the physical barrier of the wall material. Research by Felix et al. [26] showed that the gum arabic-maltodextrin microcapsules could still maintain a cinnamaldehyde retention rate of over 80% at 65°C, which was significantly better than that of the unencapsulated essential oil. Microcapsules can be compounded with other functional materials to expand application scenarios. Research by Xing et al. [27] showed that the active packaging of ZnO-coated PVC film combined with cinnamon essential oil microcapsules had an inhibition rate of over 90% against Escherichia coli and Staphylococcus aureus on the surface of fresh-cut apples, and also had antioxidant function.

4. Summary

As a natural plant resource with multiple effects, the active ingredients of cinnamon have broad application prospects in the fields of medicine, health products, food, etc. At present, certain progress has been made in the research on the active ingredients, efficacy, and delivery systems of cinnamon at home and abroad. However, further in - depth research is still needed. It is necessary to strengthen the structural identification of cinnamon's active ingredients, the research on their action mechanisms, and clinical application research to fully explore its potential medicinal value and promote the comprehensive development and utilization of cinnamon resources. In terms of delivery systems, it is necessary to optimize the preparation process of delivery systems to improve their drug - loading capacity and stability, and conduct in - depth research on the in - vivo processes of delivery systems to evaluate their safety and effectiveness, so as to provide more theoretical basis and practical guidance for the development and utilization of cinnamon.

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