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Advancements in Chemical Composition, Pharmacological Activities, and Extraction and Processing Techniques of Star Anise (*Illicium verum*)

Danna HUANG, Cong WANG, Qin WEI*, Lu CHEN*

Collaborative Innovation Center for Big Health Product Development, National Engineering Research Center for Southwest Endangered Medicinal Materials Resources Development, Guangxi Botanical Garden of Medicinal Plants, Nanning, Guangxi 530023, China

Abstract This paper systematically categorizes the primary composition of star anise (*Illicium verum*), including volatile oils, flavonoids, phenolic acids, and sesquiterpene lactones, and further analyzes the pharmacological activities, such as antibacterial, analgesic, anti-inflammatory, and antioxidant effects. Additionally, it summarizes key aspects of extraction techniques, analytical methods, and fresh material processing technologies. The objective is to provide a robust foundation for enhancing research methods and technological standards related to star anise, thereby improving resource utilization efficiency and facilitating its industrial applications.

Key words Star anise (*Illicium verum*), Chemical composition, Pharmacological activity, Extraction, Processing technique

1 Introduction

Star anise (*Illicium verum* Hook. f.) is the dried fruit of a plant belonging to the Magnoliaceae family. The fruit is gear-shaped and typically consists of eight follicles. Star anise is recognized as one of the "Ten Flavors of Guangxi" and is considered a genuine medicinal herb in the Guangxi region. In China, it is a traditional Chinese medicinal herb valued for both culinary and therapeutic properties, possessing significant medicinal and commercial importance. The utilization of star anise in China has a long history, with its origins traceable to the Song Dynasty[1]. China possesses more than 85% of the world's star anise resources and is the sole country capable of large-scale production and supply of this commodity. Notably, Guangxi accounts for over 80% of the national cultivation area and approximately 90% of the annual production, ranking first in China[2–3].

The *Chinese Pharmacopoeia* documents that star anise possesses a pungent taste and a warm nature, with its properties linked to the liver, kidney, spleen, and stomach meridians. It is traditionally used to warm yang, dispel cold, regulate qi, and alleviate pain. Clinically, it is applied in the treatment of cold hernia-related abdominal pain, low back pain due to kidney deficiency, vomiting caused by cold stomach, and cold-induced pain in the stomach duct and abdomen[2]. The *Bencao Pinhui Jingyao* (*Concise Herbal Foundation Compilation*) from the Ming Dynasty indicates that star anise is primarily utilized to treat ailments caused by cold air and various types of hernia-related pain. In the *Introduction to Medicine · Treatise on Cold Disorders*, star anise is specifically noted for its efficacy in alleviating lower back pain. Additionally, the *European Pharmacopoeia* documents that star anise possesses expectorant and antispasmodic properties. In India, star anise is utilized to stimulate appetite and act as an insect repellent. In Indonesia, it is traditionally believed to possess medicinal properties for treating insomnia and for external applications following childbirth. In Mexico and the United States, star anise is commonly employed to alleviate colic and abdominal pain in infants. In Cuba, it is used in the treatment of gastrointestinal disorders. Additionally, some studies have reported that the essential oil of star anise may be effective in managing rheumatic diseases[4]. This paper provides a comprehensive summary of the primary chemical composition, pharmacological activities, as well as the extraction, analytical, and processing techniques of star anise, in order to offer a valuable reference for the industrial application of star anise.

2 Primary chemical composition

Star anise contains a diverse array of chemical components, primarily including volatile oils, organic acids, flavonoids, and sesquiterpene lactones (Table 1). These compounds underpin the medicinal properties of star anise and contribute significantly to reducing production costs.

2.1 Volatile oils Volatile oil constitutes the primary source of the aroma of star anise[5] and represents one of the most extensively studied active composition of this plant. The majority of these compounds are biosynthesized as phenylpropanoids. The principal active composition of star anise volatile oil is anethole, which comprises approximately 80% –90% of the oil. Chemically, anethole is known as p-propenylanisole and exists in two isomeric forms: *trans*-anethole and *cis*-anethole[6]. Furthermore, the active composition include limonene, citral, estragole, anisaldehyde, aromatic alcohol, eucalyptol, as well as minor quantities of α-pinene, dipentene, methyl chavicol, borneol, methyl p-anisyl ketone, *etc.*[7]. Anethole, identified as the primary active composition, has been demonstrated to possess antibacterial, anti-inflammatory, and antioxidant properties, and is extensively utilized in the food and pharmaceutical industries.

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Danna HUANG, doctoral degree, associate chief physician. * Corresponding author. Qin WEI, master's degree, associate chief physician; Lu CHEN, master's degree, associate chief physician.

Table 1 Classification and efficacy of the primary chemical composition of star anise

Active composition	Major compounds	Efficacy
Volatile oil	Anethole, limonene, citral, estragole, anisaldehyde, eucalyptol, α-pinene, *etc.*	Antibacterial, anti-inflammatory, and antioxidant
Phenolic acids	p-Coumaric acid, gallic acid, cinnamic acid, chlorogenic acid, ferulic acid	Antioxidant, anti-obesity, antibacterial, and anti-inflammatory
Organic acids	Shikimic acid, palmitic acid, linoleic acid, oleic acid	Antiviral, anti-cancer (shikimic acid is an intermediate of oseltamivir phosphate), and metabolic regulation
Flavonoids	Quercetin, kaempferol, isorhamnetin and their glycosides (binding with D-glucose, D-xylose, L-rhamnose)	Antioxidant, and anti-inflammatory
Sesquiterpene lactones	1α-Hydroxy-3-deoxypseudoanisatin, anisatin, veranisatin A and B, 6-deoxypseudoanisatin and more than 30 derivatives	Anti-tumor, bactericidal, anti-inflammatory, and related to toxic effects
Polysaccharides	Star anise polysaccharides (a highly branched structure mainly composed of galacturonic acid)	Anti-obesity, lowering blood pressure, controlling blood sugar, antioxidation, and anti-tumor

2.2 Phenolic acids The phenolic acid compounds present in star anise primarily include p-coumaric acid, gallic acid, cinnamic acid, chlorogenic acid, ferulic acid, *etc.* [8]. These phenolic acids are distributed across different parts of the star anise plant, with the highest concentrations found in the fruit. They exhibit notable antioxidant, anti-inflammatory, and anti-obesity activities[9]. Furthermore, studies have identified additional phenolic substances, such as coumarin, apigenin, and rosmarinic acid, in the aqueous extract of star anise[10]. Together with phenolic acids, these compounds constitute the material basis underlying the diverse pharmacological activities of star anise.

2.3 Organic acids Organic acid compounds encompass shikimic acid as well as various fatty acids, including palmitic acid, linoleic acid, oleic acid, *etc.* [7]. Notably, shikimic acid serves as a crucial intermediate in the biosynthesis of diverse phytochemical composition. Its concentration varies according to the developmental stage of star anise and is predominantly localized in the fruit, with lesser amounts present in the branches and leaves. Shikimic acid is a significant metabolic product in both plants and microorganisms, contributing to the synthesis of aromatic amino acids and exhibiting anti-inflammatory and analgesic properties. Additionally, shikimic acid, an intermediate in the synthesis of antiviral and anticancer drugs, is the primary composition of oseltamivir phosphate, a widely used medication for treating influenza A. Furthermore, it is one of the most extensively studied molecules concerning the antiviral properties of star anise[11].

2.4 Flavonoids Flavonoids are one of the primary active chemical composition of star anise. The research group of Collaborative Innovation Center for Big Health Product Development optimized the extraction of total flavonoids from star anise residue, which remained after the volatile oil had been extracted, using a cellulase-ultrasonic-assisted method, and the approach achieved a yield of 14.76% [12]. Quercetin, kaempferol, and isorhamnetin are common flavonoid glycosides found in star anise; these compounds frequently form monosaccharide or disaccharide flavonoid glycosides with sugars such as D-glucose, D-xylose, and L-rhamnose[13-14].

2.5 Sesquiterpene lactones Sesquiterpene lactone compounds constitute a significant proportion of the composition found in star anise. By utilizing star anise as the raw material and applying dehulling treatment, it is possible to isolate more than 30 highly oxidized sesquiterpene lactones and their derivatives, such as anisatin, carthamic acid, *etc.* [8]. Research has demonstrated that sesquiterpene lactones and their derivatives exhibit considerable efficacy in anti-tumor activity, antibacterial effects, and anti-inflammatory responses. Furthermore, these compounds are implicated in the toxicological properties associated with star anise[15].

2.6 Polysaccharides Polysaccharide compounds derived from star anise exhibit complex structural features and diverse biological activities. Research indicates that star anise polysaccharides are predominantly extracted using propyl deep eutectic solvents and microwave-assisted techniques, achieving an extraction yield of 5.14% under optimized conditions[16]. These polysaccharides are characterized by high viscosity, substantial oil-holding capacity, and a high degree of esterification. Their primary composition includes galacturonic acid, with a highly branched polysaccharide structure[16]. Notably, these compounds have demonstrated significant therapeutic potential in managing obesity, hypertension, and diabetes[16]. Furthermore, star anise polysaccharides exhibit antioxidant and anti-tumor properties, including the inhibition of tumor growth[17].

3 Pharmacological activities

3.1 Antioxidant effects Luís *et al.* [18] assessed the antioxidant activity of star anise essential oil through a 1,1-diphenyl-2-picrylhydrazyl (DPPH) radical scavenging assay. The findings demonstrated that star anise essential oil exhibited potent antioxidant activity, with a median inhibition concentration (IC_{50}) of 3.46%. This antioxidant effect was hypothesized to be associated with the high concentration of phenylpropanoids, particularly *trans*-anethole, which constituted 92.2% of the oil. Studies have demonstrated that *trans*-anethole and its derivative, thioanisole, enhance the body's antioxidant capacity by increasing intracellular glutathione levels and augmenting the activity of glutathione S-transferase (GST)[19]. Cai *et al.* [20] examined the DPPH and ABTS radical scavenging activities of star anise volatile oil. Their findings demonstrated that the oil exhibited moderate DPPH scavenging activity, which intensified with increasing co-permeation. Although *trans*-anethole has been identified as a principal antioxidant composition, its potential involvement in more complex antioxidant mechanisms, such as mitochondrial function protection and DNA damage repair, remains unclear.

3.2 Anti-inflammatory and analgesic effects Studies have demonstrated that the methanol extract of star anise significantly inhibits the production of pro-inflammatory cytokines, including tumor necrosis factor-α (TNF-α) and interleukin-1β (IL-1β), thereby exerting anti-inflammatory effects[21]. Additionally, these components mitigate pain by modulating signal transduction within the nervous system[22]. Tuseef *et al.* [23] demonstrated that methanol, ethanol, and aqueous extracts of star anise exhibited significant analgesic, antipyretic, and anti-inflammatory effects at varying doses. These effects were evaluated using hot plate analgesic models, yeast-induced fever models, and plantar edema models in rodents, and were found to be dose-dependent. Additionally, the study measured inflammatory factors such as IL-6 and IgE, thereby providing initial insights into the biological mechanisms underlying the anti-inflammatory properties of star anise. The anti-inflammatory properties of the active composition in star anise were investigated using various animal models, including the hot plate method (pain), plantar edema (inflammation), and fever models, and the analgesic and antipyretic effects of star anise were thoroughly examined. However, limited research has investigated the impact of their composition on inflammatory signaling pathways, such as NF-κB, MAPK, and TLR4, or examined whether long-term administration may result in immunosuppression or adverse effects.

3.3 Antibacterial effects A double-blind, randomized crossover clinical trial involving 50 participants assessed the effects of star anise mouthwash on oral health. The findings demonstrated that star anise mouthwash was significantly more effective than placebo in reducing the gingival index, nipple bleeding index, and the number of oral microorganisms. These results suggest that star anise possesses astringent and antibacterial properties, indicating its potential application in oral health care[24]. Salem *et al.* [25] demonstrated that the methanol extract of star anise exhibited significant inhibitory and separation effects on biofilm formation by multidrug-resistant and highly virulent *Acinetobacter baumannii* AB5057 and methicillin-resistant *Staphylococcus aureus* (MRSA) strain USA300. Furthermore, local *in vivo* application of the extract reduced bacterial load in MRSA-infected skin lesions. These findings suggest that the polar composition of star anise may serve as a virulence-targeting strategy against persistent infections and hold potential for development as topical antibacterial agents in the treatment of *S. aureus* skin infections. The antibacterial activity of star anise against pathogenic bacteria primarily involves the synergistic degradation of bacterial cell walls by multiple antibacterial components, disruption of the cytoplasmic membrane, or denaturation of membrane proteins. These actions lead to the leakage of intracellular substances such as glucose, proteins, and DNA, thereby impairing anabolic metabolism and ultimately causing bacterial or fungal cell death[26]. Currently, the majority of research concentrates on drug-resistant bacteria, such as MRSA, due to their significant practical relevance. Nevertheless, given the increasing diversity of bacterial infections, investigations into the antibacterial effects of star anise on other bacterial species are ongoing. These studies aim to establish a scientific foundation for the application of star anise in antibacterial treatments and to support its further development as a natural antibacterial agent.

3.4 Antiviral effects Li *et al.* [27] isolated borneol coumarate from star anise, which exhibited potent antiviral activity. Its median inhibitory concentration against the H1N1 influenza A virus was more effective than that of tamiflu and ribavirin. The research team at the Collaborative Innovation Center for Big Health Product Development investigated the potential mechanisms underlying the preventive and therapeutic effects of star anise volatile oil against novel coronavirus pneumonia using network pharmacology approaches. Their findings suggest that the volatile oil may exert its effects through antiviral, anti-inflammatory, immunomodulatory, and cardiovascular protective pathways[28]. Torres *et al.* [29] investigated the antiviral and cytotoxic activities of a novel coronavirus pseudovirus by assessing its cellular entry and performing XTT assays in HeLa cells expressing human angiotensin-converting enzyme 2. Their findings indicate that star anise volatile oil possesses potential inhibitory effects against the novel coronavirus.

3.5 Anti-tumor effects Studies demonstrated that star anise significantly inhibited tumor-induced migration of human umbilical vein endothelial cells and tubule formation. Additionally, it suppressed tumor-induced angiogenesis *in vivo* by reducing the levels of angiogenic factors within tumors, indicating its potential utility in the treatment of metastatic malignant tumors[30]. In chronic myeloid leukemia cells, treatment with star anise, either alone or in combination with imatinib, significantly reduced the expression of the *Bcr-Abl* fusion gene and exhibited anti-leukemic activity[31]. Additionally, nanoparticles of star anise extract were synthesized by loading onto chitosan. These nanoparticles demonstrated a significant, dose-dependent reduction in cell viability in the NCl-H460 lung cancer cell line[32]. Another study demonstrated that star anise inhibited the proliferation of human breast cancer MCF-7 cells[33]. Currently, research on the anti-tumor effects of star anise has progressed at the cellular level, revealing broad-spectrum antitumor activity. Furthermore, more detailed investigations into its anti-tumor efficacy have been conducted utilizing nano-formulations. However, studies focusing on its molecular mechanisms of action and the development of novel dosage forms remain relatively limited.

3.6 Regulation of sugar and lipid metabolism In a study, rats rendered obese through a high-fat, high-sugar diet exhibited significantly reduced weight gain, diminished oxidative stress markers, and decreased adipose tissue following intervention with star anise, suggesting that star anise has antioxidant and anti-obesity properties[8]. In another study, star anise was shown to decrease blood glucose, urea, lipid concentrations, liver function indices, and renal advanced glycation end products (AGEs) in streptozotocin-induced diabetic rats. These findings indicate its potential utility as an adjunctive treatment for diabetes and the inhibition of non-enzymatic glycation reactions, thereby alleviating associated complications[34]. Alias *et al*.[16] extracted star anise polysaccharides utilizing a propanol-based eutectic solvent combined with a microwave-assisted method. The resulting acidic pectin exhibited gel-like properties, a highly amorphous structure, elevated galacturonic acid content, and a highly branched polysaccharide structure. Furthermore, it demonstrated significant inhibitory effects on pancreatic lipase (86.67%), angiotensin-converting enzyme (73.47%), and α-glucosidase (82.33%), indicating its potential application in blood glucose regulation for diabetes management.

3.7 Other effects Several clinical case studies conducted between 2004 and 2021 examined three infants exposed to star anise. The findings indicated that star anise might be effective in treating infantile colic, but it also exhibited neurotoxic effects. These neurotoxic symptoms varied from mild irritability and vomiting to severe convulsions, primarily resulting from contamination of Chinese star anise with Japanese star anise, which contains neurotoxins. Nevertheless, in the majority of cases, no long-term neurological sequelae were observed following conservative treatment[35].

Star anise exhibits a range of pharmacological effects, but clinical studies investigating these effects remain relatively limited. Current research predominantly emphasizes its chemical composition and their potential pharmacological activities. Future investigations are anticipated to focus on shikimic acid and other bioactive compounds derived from star anise for the development of novel antiviral agents targeting influenza. Furthermore, its antibacterial and antifungal properties suggest potential applications as a natural food preservative and as an ingredient in pharmaceutical formulations. Additionally, the notable antioxidant capacity of star anise may be utilized in the development of natural products, including antioxidant supplements and skincare formulations.

4 Extraction and processing techniques of commonly used chemical composition

4.1 Common extraction methods for various pharmacological chemical substances Different extraction methods possess distinct characteristics regarding extraction efficiency, solvent residue, environmental impact, and scope of application. In practical applications, the optimal method should be selected comprehensively, taking into account the polarity and stability of the target composition as well as the intended purpose of the product (Table 2).

Table 2 Comparison analysis of extraction methods for star anise

Extraction method	Advantage	Disadvantage	Scope of application
Steam distillation	Pure, environmentally friendly, and safe	Higher cost, easy degradation of heat-sensitive composition	Essential oil extraction
Molecular distillation	Low-temperature extraction, less likely to damage composition, straightforward operation, low energy consumption, and environmentally friendly	Expensive equipment	High-end essential oil separation
Organic solvent extraction	Straightforward operation, and low cost	Large solvent consumption, and low extraction efficiency	Laboratory small-scale extraction
Soxhlet extraction	Straightforward operation, low cost, and high extraction rate	Long duration, large consumption of solvent, easy degradation of heat-sensitive composition due to exposure to high-temperature heating	Laboratory high-purity extraction
Supercritical CO_2	No solvent residue	Complex process	Drug and food-grade extraction
Ultrasonic extraction	Straightforward operation, and low extraction process costs	Low extraction rate	Laboratory small-scale extraction
Subcritical fluid n-butanol extraction	Protection of heat-sensitive composition by exposure to low temperature, and reservation of aromatic characteristics	New process, high requirements on equipment	High-value essential oil extraction
Enzyme-assisted extraction	Highly effective at breaking down cell walls, environmentally friendly and gentle, and minimal solvent usage	High cost of enzymes, complex process optimization, and need to integrate with other techniques	Need high extraction efficiency scenarios

4.1.1 Steam distillation. The star anise oil extracted via steam distillation exhibits minimal residue and contamination. Yu Caiyun *et al*.[36] employed steam distillation using water as the solvent and conducted a four-factor, three-level orthogonal experiment, selecting particle size of crushed star anise, soaking time, solid-liquid ratio, and distillation time as variables. They compared the extraction rates of star anise oil across different factors and levels. The results indicated that all four factors influenced the extraction rate, *trans*-anethole content, and overall yield of star anise to varying extents. This method is commonly utilized for the extraction of volatile oils. However, the application of high-temperature distillation may cause degradation of certain heat-sensitive composition. Although the method is environmentally friendly and safe, it is limited by low economic efficiency. Therefore, optimizing the four factors under appropriate conditions is essential to enhance production efficiency and maximize economic benefits in star anise oil extraction.

4.1.2 Molecular distillation. Molecular distillation is an environmentally friendly technology that exploits differences in the mean free path of molecules among various substances. Operating under high vacuum conditions, this technique enables separation at temperatures substantially lower than the material's boiling point. The process offers several advantages, including short heating durations, elimination of boiling, straightforward and continuous operation, low energy consumption, and environmental sustainability[37]. Yin Tuanzhang *et al.*[38] employed molecular distillation to extract star anise oil, successfully isolating its light composition. This method is well-suited for producing high-purity essential oils and effectively minimizes impurity interference. Nevertheless, the associated equipment costs are relatively high, limiting its application primarily to the industrial-scale production of high value-added products within large enterprises.

4.1.3 Organic solvent extraction. Lu Jiahui *et al.*[39] selected acetone as the solvent and considered extraction time, solid-liquid ratio, and extraction temperature as variables to optimize the extraction process using the response surface method. Using the yield of essential oil as the response variable, the optimal conditions for extracting star anise oil were determined. Overall, although the organic solvent extraction method is simple to operate and cost-effective, it presents challenges such as high solvent consumption and low extraction efficiency, which adversely affect the oil yield of star anise.

4.1.4 Soxhlet extraction. Soxhlet extraction is a classic solvent extraction technique, commonly employing ethanol as the solvent. Research indicates that Soxhlet extraction achieves the highest yield, particularly when 99.7% ethanol is utilized, with extraction rates reaching up to 25.51%[40-41]. Furthermore, Soxhlet extraction effectively preserves the biological activity of essential oils[41].

4.1.5 Supercritical CO_2 extraction. Supercritical CO_2 extraction offers several advantages, including a straightforward process, low operation temperatures, high separation efficiency and rate, absence of solvent residues, and prevention of extract solidification at room temperature. Numerous studies have documented the extraction of star anise oil using this method[42-44]. Compared to traditional solvent extraction, supercritical CO_2 extraction is more environmentally friendly and is well-suited for obtaining high-purity composition. Nevertheless, the associated equipment costs are relatively high, making this technique more appropriate for large-scale industrial applications.

4.1.6 Ultrasonic extraction. Ultrasonic extraction is extensively utilized in the domain of traditional Chinese medicine. This technique leverages the unique effects of ultrasonic waves, including intense cavitation, vibration, and mechanical disruption, which facilitate the destruction of cells within Chinese medicinal materials. Consequently, solvent penetration into the cells is enhanced, thereby accelerating the dissolution and extraction of active composition. For instance, Lee *et al.*[45] employed an ultrasonic extraction method using 81% ethanol at 63 ℃ for 15 min to isolate anisaldehyde and anethole, achieving maximum extraction yields of 0.402% and 7.996%, respectively. Similarly, Li Ping *et al.*[46] utilized ultrasonic extraction with ethyl acetate as the solvent to obtain volatile oil from star anise, reporting an extraction yield of 23.89%. Their findings also indicated that temperature significantly influenced the mass loss of star anise volatile oil.

4.1.7 Subcritical fluid n-butanol extraction. Subcritical fluid extraction is an emerging technology that operates at relatively low temperatures, thereby effectively preserving heat-sensitive composition. Research indicates that the yield of star anise essential oil obtained through subcritical fluid extraction is approximately 7.77%, and the extracted oil exhibits enhanced aromatic properties[41].

4.1.8 Enzyme-assisted extraction. The enzyme-assisted extraction method leverages the catalytic activity of enzymes to enhance extraction efficiency. This technique is commonly applied to improve the extraction of macromolecular substances, such as polysaccharides[16]. It has been reported that the yield of *trans*-anethole obtained through enzyme-assisted extraction alone is 40.90%, whereas combining microwave-assisted and ultrasonic-assisted extraction methods can increase the yield to 56%[47].

In conclusion, among the eight commonly employed extraction methods, steam distillation is environmentally friendly and safe, but it is associated with high production costs and is influenced by numerous factors. Molecular distillation offers a simple and continuous operation with low energy consumption and environmental benefits. Nevertheless, it is effective only for extracting crude extracts and is primarily suitable for large-scale industrial production. Although organic solvent extraction and Soxhlet extraction methods are straightforward, cost-effective, and appropriate for laboratory-scale extraction, they are characterized by high solvent consumption and low extraction efficiency, which adversely affect the oil yield of star anise and contribute to environmental pollution. Supercritical CO_2 extraction offers several advantages, including a straightforward process, low operation temperatures, high separation efficiency and rate, absence of solvent residues, and prevention of extract solidification at room temperature. Nevertheless, the extraction equipment and raw materials involved are more costly compared to alternative methods. Ultrasonic extraction and subcritical fluid extraction are effective in preserving heat-sensitive composition; the former is suitable for rapid extraction, whereas the latter excels in retaining unique aromas. However, both techniques require further process optimization to facilitate industrial-scale application. Enzyme-assisted extraction significantly enhances the yield of polysaccharides and flavonoids through enzymatic hydrolysis of cell walls. Despite this, challenges related to enzyme activity stability and cost remain to be resolved. This method represents a promising avenue for the future biotechnological development of star anise.

4.2 Common analytical methods for pharmacological chemical substances The analysis of chemical substances and the structural identification of star anise primarily involve chromatographic and spectroscopic techniques. These methods are employed to identify and quantify the chemical composition present in star anise.

4.2.1 Chromatographic analysis. The chemical composition of star anise, as analyzed by high-performance liquid chromatography (HPLC), is relatively complex, with trans-anethole and shikimic acid identified as the most abundant and characteristic composition. The *Chinese Pharmacopoeia* (2020 edition) quantifies only the *trans*-anethole content in star anise using gas chromatography (GC) methods, without including evaluation criteria for water-soluble composition. Peng Shangui *et al.* [48] developed a HPLC method for the simultaneous quantification of shikimic acid and *trans*-anethole to enable more scientific and rational quality control of star anise. Similarly, Ou Min *et al.* [49] employed HPLC to analyze four organic acids in star anise and established a method for determining shikimic acid, protocatechuic acid, p-hydroxybenzoic acid, and p-methoxybenzoic acid, which can be utilized for the quality control of star anise. Wang Qin *et al.* [50] analyzed the gas-phase spectra and chemical composition of star anise extracts obtained via steam distillation, organic solvent extraction, and supercritical CO_2 extraction using gas chromatography-mass spectrometry (GC-MS). The study revealed that while the chemical composition of star anise oil extracted by the three methods were similar, the extracts obtained through organic solvent and supercritical CO_2 extraction contained a greater variety of chemical composition. Zheng Yanfei *et al.* conducted an analysis of the chemical composition of volatile oils extracted from star anise shells and seeds using GC-MS. Their findings revealed the presence of 32 common compounds in the volatile oil profiles of both star anise shells and seeds, which accounted for 94.03% and 94.68% of the total volatile oil content, respectively. The composition profiles of the volatile oils from the shells and seeds exhibited minimal differences. Anethole was identified as the predominant compound in both samples, followed by estragole.

Ultra-high performance liquid chromatography-tandem mass spectrometry (UHPLC-MS/MS) can be employed to simultaneously quantify three therapeutic flavonoids and the neurotoxic compound anisomycin in star anise. This technique enables rapid separation and accurate quantification of multiple marker compounds through the use of heavy isotope compounds as internal standards[51].

Gas chromatography-isotope ratio mass spectrometry (GC-IRMS) is an effective analytical technique for verifying the authenticity of star anise essential oil, particularly in detecting adulteration involving anethole[52].

In the *Chinese Pharmacopoeia* (2020 edition), star anise was identified and analyzed through thin-layer chromatography (TLC). The results indicated that star anise samples exhibiting spots of the same color, ranging from orange to orange-red, could be accurately identified as star anise.

4.2.2 Spectral analysis. Fourier transform infrared spectroscopy (FTIR) is a widely employed analytical technique for structural identification. It is utilized to analyze the chemical bonds and functional groups present in star anise essential oil, including benzene rings, carbonyl groups, and aromatic ether bonds[41].

Nuclear magnetic resonance (NMR) spectroscopy is a widely employed analytical technique for structural identification. It is particularly useful for identifying the primary compounds in star anise essential oil and for providing detailed molecular structural information[53].

4.2.3 Other analytical methods. Electronic nose analysis (E-Nose) is a technique used to detect samples by analyzing their volatile odor compounds. Given that star anise oil possesses a distinctive volatile aroma, this method is particularly well-suited for its identification. A fingerprint map of star anise essential oil can be developed to represent the primary characteristics of the subject from multiple perspectives. Subsequently, one-way analysis of variance, principal composition analysis, and linear discriminant analysis can be employed to perform cluster analysis on the detection results, facilitating the selection of optimal parameters. Finally, a methodological investigation is conducted using the selected parameters to assess the reliability of the instrument under these conditions. The obtained results can be applied to subsequent qualitative and quantitative analyses of star anise oil[52].

The potential distribution and quality of star anise under climate change was evaluated by integrating two-dimensional chromatography technology, the MaxEnt model, and chemical analysis. The results indicated that environmental factors, particularly soil pH, were critical determinants of its distribution. Furthermore, projections suggested a northward shift in suitable habitats in the future. Additionally, potential chemical markers were identified to differentiate the quality of star anise from various origins, thereby providing a scientific foundation for resource conservation, site selection for cultivation, and quality control of star anise[54].

4.3 Processing techniques

4.3.1 Traditional processing techniques and their current situation. The traditional processing of star anise primarily involves drying the harvested fruit, with the final product predominantly available as dried fruits. Currently, in China, the processing of dried star anise is largely conducted by individual farmers and small-scale workshops. Traditional methods, including direct sun-drying, fixation followed by sun-drying, wood-fired drying, and basic earthen bed drying, are predominantly employed[3].

The method of fixation followed by sun-drying offers advantages such as low production costs and favorable coloration of dried fruits, making it a widely employed drying technique in current production regions. However, this method presents notable limitations. Specifically, it is highly dependent on weather conditions, manual labor, and extensive drying areas. Delays in the drying process can lead to mold growth on star anise, adversely affecting its appearance and food safety. Additionally, this method is labor-intensive, time-consuming, and exhibits low operational efficiency[3].

Freshly harvested wet star anise must undergo processing procedures, including fixation, sun-drying, or baking, prior to entering the commercial market. In practice, sulfur fumigation is frequently employed to treat fresh star anise fruits to inhibit mold growth and enhance coloration. However, this method can result in residual sulfur dioxide in star anise products. Prolonged excessive oral exposure to sulfur dioxide may adversely affect human health by irritating the mucous membranes of the respiratory and digestive tracts, inducing gastrointestinal symptoms such as nausea and vomiting, and potentially increasing the risk of asthma exacerbations and brain tissue damage[55]. Consequently, despite the high efficiency of traditional sulfur fumigation, it poses considerable health risks. Therefore, optimizing fumigation techniques or developing alternative treatment methods has become a critical area of research.

4.3.2 Modern processing techniques. In recent years, with technological advancements, certain processing enterprises have initiated the use of large-scale automated mechanical equipment for the mass drying of star anise. While this has led to increased production efficiency, these enterprises continue to encounter technical challenges related to maintaining and enhancing the color, appearance, and internal quality of dried star anise products.

Microwave drying is a technique that employs microwave energy to heat materials. During this process, microwave radiation penetrates the material, inducing rapid oscillation of polar molecules, such as water molecules, under the influence of high-frequency electromagnetic fields. This molecular movement generates frictional heat, which raises the internal temperature of the material, facilitating the evaporation and removal of water. Since microwaves can directly interact with the interior of materials, microwave drying is generally more efficient than conventional hot air drying, achieving faster drying rates while preserving the nutritional content and flavor of the materials[56]. A study employed continuous microwave drying in combination with hot air drying to process star anise, investigating the effects of varying microwave power levels and hot air temperatures on several parameters, including star anise oil content, color difference, compound composition, sensory attributes, and the microstructure of star anise powder[57]. The findings indicated that, compared to traditional methods such as natural sun-drying and fixation followed by sun-drying, this approach enhanced drying efficiency, effectively removed moisture, reduced drying time, minimized the degradation of heat-sensitive compounds, and preserved the original aroma and quality of star anise. These results suggest significant potential for the application of this method in modern production processes[57].

Chen Lu *et al.*[58] employed an ozone pretreatment method. Following harvesting and net selection, the samples were immediately exposed to ozone at a rate of 2 – 5 g/h. Subsequently, the samples underwent drying, grading, and packaging processes, successfully extending the storage duration of star anise without the use of sulfur fumigation. Furthermore, the residual sulfur dioxide levels complied with the GB 2760-2014 *National Food Safety Standard for the Use of Food Additives*, and other evaluation metrics were comparable to or slightly superior to those observed in products processed using conventional methods. The ozone pretreatment method can prolong the storage duration of fresh star anise fruits without the use of harmful chemicals. It significantly enhances the quality of star anise products that cannot be processed promptly due to inclement weather, effectively reduces microbial contamination, and minimizes chemical pollution during food processing. This method is characterized by its simplicity, safety, practicality, and suitability for widespread application.

4.3.3 Sterilization techniques. The primary sterilization method employed for star anise is irradiation technology, which is recognized as an effective sterilization technique. Application of an irradiation dose ranging from 2 to 10 kGy to star anise has been demonstrated to extend its shelf life and achieve microbial decontamination. Furthermore, research indicates that irradiation not only effectively sterilizes but also enhances the accumulation of polyphenols in star anise, with a particularly notable increase in flavonoid content[59].

4.3.4 Packaging techniques and their impacts. A study investigated the effects of four packaging methods—transparent sealed bags, transparent plastic bags, black light-proof sealed bags, and woven bags—on the storage quality of dried star anise over a one-year period. The findings demonstrated that sealed packaging (both transparent and black sealed bags) exhibited significantly superior moisture resistance compared to non-sealed packaging (woven bags and transparent plastic bags). Among these, transparent sealed bags preserved the best color quality. Additionally, black light-proof sealed bags effectively minimized the degradation of shikimic acid, volatile oils, and *trans*-anethole. GC-MS combined with principal composition analysis revealed that samples stored in black sealed bags contained the highest levels of volatile compounds, followed by those in transparent sealed bags. In conclusion, black light-proof sealed bags is the optimal packaging method for storing dried star anise at room temperature[60].

5 Prospects

Star anise, characterized by its diverse chemical composition and a range of biological activities—including antioxidant, anti-inflammatory, and antibacterial effects—serves as a crucial basis for the development of novel pharmaceuticals and health products that integrate both nutritional and medicinal functions. Advances in quality analysis techniques have facilitated its standardized production, while improvements in processing techniques have enhanced utilization efficiency, flavor, and stability, thereby addressing market demands for high-quality pharmaceutical and food products. Despite considerable progress in star anise research, further breakthroughs are required in the efficient application of its active compounds, comprehensive elucidation of pharmacological mechanisms, and the development of green processing methods.

Future research should focus on further elucidating the molecular mechanisms involved, employing omics technologies and molecular simulation methods to systematically analyze the modes of action of key composition, including *trans*-anethole and sesquiterpene lactones, in antioxidant and inflammatory regulation. Additionally, long-term safety evaluations are necessary to establish a foundation for their practical applications. Moreover, the development of novel drug delivery systems incorporating composition such as star anise polysaccharides is anticipated to enhance bioavailability. This approach holds particular promise for applications in areas where food and medicine share common origins, such as diabetes management and immune regulation, thereby supporting advancements in the big health industry. At the level of technological innovation, it is imperative to transcend the limitations inherent in individual extraction methods by investigating the combined application of molecular distillation and supercritical CO_2 extraction technologies to achieve efficient separation and enrichment of active composition. Furthermore, the potential optimization of techniques such as microwave-ozone co-drying should be explored to enhance processing efficiency while preserving nutritional value and quality. Additionally, the development of enzyme engineering and green processes—such as the integration of immobilized enzymes with supercritical extraction—may facilitate efficient and low-consumption production. Finally, the industrial production of artemisinin via engineered yeast can serve as a case study; through synthetic biology and metabolic engineering, yeast can be modified to produce shikimic acid, thereby addressing the raw material supply bottleneck associated with "oseltamivir phosphate" production. Furthermore, enhancing the quality control system remains an urgent priority. The current standards consider *trans*-anisic acid and shikimic acid as primary indicators. Moving forward, it is essential to develop multi-composition combined detection methods, such as HPLC and GC-MS, to enable comprehensive standardized management throughout the entire production chain, from raw materials to final products.

With the ongoing advancement of research into the chemical composition, pharmacological activities, quality analysis, and processing techniques of star anise, future investigations should emphasize an integrated approach encompassing "composition, mechanisms, techniques, and product development". This strategy aims to facilitate the transition of star anise from its traditional use as a spice to applications in precision medicine and functional foods. Consequently, star anise is anticipated to serve as a model for the research and development of natural medicines, thereby providing new impetus for the modernization of traditional Chinese medicine and the advancement of the global health industry.

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