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Research Progress on the Stability and Degradation Mechanism of *Cistanche deserticola* Active Compounds During Different Maturity, Preservation, and Processing

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ABSTRACT

Cistanche deserticola (CD) Y. C. Ma is a well-known tonic medicinal material, and its clinical value and industrial development are highly dependent on the integrity of core pharmacodynamic components (such as phenylosides and polysaccharides). This article systematically reviews the impact of three key links: harvest maturity, postharvest preservation methods, and processing methods on the quality of CD and their internal relationships in order to provide a scientific basis for building a full-chain quality control system. The maturity is the basis of quality formation. The early bud stage of CD is the double-peak window of phenylethanoid glycosides (PhGs) and active polysaccharides, which is the best harvest point of first-class medicinal materials. Storage and preservation methods are the key to maintaining chemical potential at harvest time. The combined use of low temperature, modified atmosphere, packaging, and preservatives can maintain stable quality. Processing methods are the ultimate directional shaper of quality. Modern processing methods such as steaming and drying processes can improve drying efficiency, enhance the conversion of active ingredients, and save energy. This study provides a theoretical basis and methodological reference for establishing an integrated collaborative control system for "harvest-preservation-processing" of CD, and has practical value for promoting the engineering transformation of postharvest scientific and technological achievements of CD and improving the overall efficiency of the medicine and food homologous industrial chain.

1 | Introduction

Cistanche deserticola (CD) Y. C. Ma (Chinese name: *Roucongrong*) is an important characteristic medicinal resource in the arid area of northwest China. Its unique phenylethanoid glycosides (PhGs), such as echinacoside (ECH), acteoside (ACT), iridoid, and polysaccharides are the material basis for giving it pharmacological activities such as antiaging, neuroprotection, and immunoregulation [1]. The content, proportion, and existence form of these active ingredients together constitute their "chemical integrity," which directly determines the final quality and efficacy of the medicinal material. However, these pharmacodynamic substances have significant chemical instability: PhGs contain multiple phenolic hydroxyl groups and are easy to oxidatively degrade; iridoids are sensitive to heat and prone to hydrolysis and molecular rearrangement; polysaccharides are susceptible to enzymatic hydrolysis and microbial metabolism [2]. Therefore, maintaining chemical

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integrity during the postharvest process is the scientific core to ensure the quality of CD, and the transformation process of these ingredients from the field to the product is easily affected by many aspects such as harvesting, postharvest treatment, and processing. Maximizing and standardizing the quality of CD medicinal materials is a core challenge faced by the industry and scientific research community.

Although wild resources are on the verge of exhaustion due to over-exploitation and are included in Appendix II of CITES, and the scale of artificial cultivation continues to expand, problems such as low industrial standardization and uneven quality have become increasingly prominent [3]. Most of the existing literature focuses on the optimization of cultivation techniques, identification of chemical components, and evaluation of pharmacological activities, while research on the systematic mechanism of how postharvest handling affects its chemical integrity is relatively scarce. Studies have shown that: (1) The content of active ingredients of CD changes dynamically with the growth and development stage [4]. Early or late harvesting will lead to insufficient accumulation or decomposition and transformation of effective substances. Currently, there is a lack of optimal harvesting based on chemical integrity indicators. Scientific criteria for judging the period and the quantitative relationship of "ripenity-ingredient accumulation-efficacy" have not yet been established. (2) Postharvest preservation is a key buffer for maintaining chemical integrity. Fresh CD has a water content of as high as 70%–80%, and it still undergoes active physiological metabolism after harvest. PhGs are prone to enzymatic browning and oxidative degradation under the catalysis of polyphenol oxidase (PPO) and peroxidase (POD). At the same time, microbial reproduction leads to the transformation of secondary metabolites. Although modern preservation technologies such as low-temperature storage, modified atmosphere packaging (MAP), and preservative coating treatment are mature in the field of fruits and vegetables [5, 6], a postharvest technical system for the chemical stability protection of CD has not yet been established. There is a lack of systematic research on the dose-effect relationship between temperature, humidity, gas, and active ingredient retention. (3) Parameters such as temperature, time, and method during the processing and drying process directly affect the retention rate of heat-sensitive active ingredients. The traditional drying and drying method have a long cycle, and PhGs suffer oxidation losses under long-term exposure to light and oxygen; improper control of hot air drying (HAD) temperature leads to pyrolysis of iridoid glycosides; while vacuum freeze drying (FD) can maximize the extent to maintain the quality of medicinal materials. However, the cost is high, energy consumption is large, and industrial application is limited [7]. At present, there is a lack of comprehensive evaluation of the simultaneous retention effect of different drying methods on multiple active ingredients, and it is difficult to establish a scientific process selection model between quality and cost.

To sum up, understanding how harvest maturity, postharvest preservation, and processing methods regulate the chemical integrity of CD is not only a scientific problem to explain its quality variation mechanism but also an industrial demand to establish standardized production technical specifications and realize quality control. Current domestic and foreign research is characterized by "more empirical descriptions, less mechanism research, more single technologies, and less system integration" (Table 1). This article comprehensively analyzes its impact laws and mechanisms on the quality of CD from three dimensions: harvest maturity, postharvest preservation methods, and processing methods in order to provide theoretical reference for establishing scientific and reasonable harvesting and processing technical specifications and improving the quality standardization level of medicinal materials and promote the sustainable development of the CD industry.

2 | Methodology

This article uses "*Cistanche deserticola*," "growth period," "preservation," "wine steaming," "Maturity," "Fresh-keeping," "Processing methods," and other keywords as keywords and searches relevant literature published in the past 20 years in databases such as China Knowledge Network, Wanfang Data, VIP, PubMed, SpringerLink, etc., to discuss the harvesting, processing, and preservation methods of CD. A total of 208 related literatures were retrieved, of which 73 were valid literatures.

3 | Main Active Ingredients and Pharmacological Effects of CD

The main active ingredients of CD include PhGs, CD polysaccharides (CDPs), iridoids, and lignans. Through the "multicomponent-multitarget mechanism" (such as regulating NF-κB, TLR4, and other pathways), it comprehensively exerts multieffect synergistic effects such as tonifying kidney, relaxing bowel, and enhancing immunity and has become the core medicine for traditional Chinese medicine in treating kidney-yang deficiency and elderly deficiency.

3.1 | PhGs

PhGs are the most characteristic pharmacodynamic substances of CD. Representative substances include ECH, ACT, Tubuloside B (Tub B), etc. It has antichronic altitude sickness, antioxidation, antifatigue, anti-liver damage, antidementia, anti-inflammatory, anticancer, immunoregulation, antibacterial, antitumor, antiviral, and other effects [2]. Studies have found that ACT can inhibit iron death in neurons by activating the Nrf2-mitochondrial autophagy signaling pathway, protect dopaminergic neurons, relieve behavioral and cognitive disorders in vitro and in vivo Parkinson's disease models, and is beneficial for the treatment and prevention of Parkinson's disease [9]. ECH has a significant antidepressant effect in the poststroke depression (PSD) model. ECH upregulates Nrf2 by promoting its acetylation, thereby enhancing the transcriptional activity of BDNF. This, in turn, activates the BDNF/TrkB signaling axis, leading to the inhibition of oxidative stress and apoptosis, as well as the activation of the antioxidant system, thereby improving PSD symptoms in rats [10]. Tub B inhibits the migration of liver cancer cells by inhibiting the Hippo-YAP pathway. Tub B reduces the expression of transcriptional target genes downstream of the Hippo pathway, including CTGF, CYR61, and N-cadherin. Tub B increases the phosphorylation of YAP at the S127 site, which contributes to the cytoplasmic localization of YAP and eliminates YAP nuclear accumulation in Hep3B cells [11]. In recent years, there have been many studies on the pharmacological effects of PhGs,

TABLE 1 | Research status at home and abroad on harvesting maturity, preservation methods, and processing methods.

Direction	Domestic research status	Current situation of foreign research
Harvest maturity	Wang et al. [1] analyzed the dynamic changes of active ingredients during the entire growth period of CD. However, existing research mostly focuses on the comparison between spring and autumn, lacking refined research on the growth years (2–4 years old), different phenological stages and the synergy of environmental factors, and has not yet established the optimal harvest period based on chemical integrity quantitative judgment model.	CD is also distributed in Central Asia and the Mediterranean region, but relevant research mainly focuses on resource survey and taxonomy, and research on quality regulation on harvest maturity is relatively scarce. In recent years, South Korean scholars have paid attention to the quality evaluation of imported CD, but most of them follow the standards of the China Pharmacopoeia and lack original research.
Storage and preservation method	The research on postharvest preservation technology of CD started late, and at present, the experience of fruit and vegetable preservation is mostly used for reference. Zhai et al. [8] used chemical preservatives and biological preservatives combined with low-temperature storage to delay the quality deterioration of fresh Cistanche deserticola. Some companies try modified atmosphere packaging (MAP) and chitosan coating treatment, but lack systematic process parameter optimization and mechanism research.	Most postharvest physiological research on parasitic plants focuses on species such as sandalwood and nutmeg, and little attention has been paid to CD. Israeli scholars have accumulated some accumulation in postharvest water conservation of desert plants, but their direct application value is limited. Japan is leading the way in preservation technologies of traditional Chinese medicinal materials (such as ice-temperature storage and biologically-derived preservatives), but no specific research on CD has been reported. At present, there is a lack of special preservation technology designed for CD's high moisture content, high enzyme activity, and high nutritional characteristics in the world.
Processing method	Research on CD processing has undergone a transformation from traditional experience to modern technology. Traditional drying and drying methods are gradually being replaced due to long cycles and large losses. Although vacuum freeze-drying technology can retain more than 90% of the active ingredients, it has high cost, low production capacity, and limited industrial application. In recent years, heat pump drying, microwave vacuum drying, and combined drying technologies have begun to attract attention, but research on multifactor coupling optimization and quality-cost balance models is insufficient.	The application research of drying technology in the field of Chinese herbal medicine is more active in Europe. German and Swiss scholars have accumulated a deep accumulation in low-temperature vacuum drying and heat pump drying technologies, but most of the research objects are local medicinal plants (such as chamomile and valerian). The U.S. FDA's quality control requirements for botanical drugs have promoted the development of chemical stability research during the drying process, but specific studies on CD are rare. International research on drying kinetics and component retention mechanism of high-value parasitic medicinal materials is still blank.

involving a variety of diseases (such as osteoporosis, Parkinson's disease, cardiovascular and cerebrovascular diseases, etc.) and are potential medicinal ingredients.

3.2 | Polysaccharides

CDPs have antidepressant, antiaging, antioxidant, anti-inflammatory, intestinal flora regulation, antiosteoporosis, immunomodulatory, and other activities [12]. CDPs are mainly composed of mannitol (antifatigue, relaxing the intestines and relaxing the bowel), arabinose (hypoglycemic), glucose (replenishing energy), galacturonic acid (anti-inflammatory), etc. Its physical and chemical characteristics depend on the monosaccharide composition, molecular weight, and chemical structure. Studies have found that CDPs has the potential to prevent and treat ALD by regulating the gut–liver axis. CDPs downregulates the level of Keap1 protein in the liver, resulting in an increase in the expression of Nrf2 protein, effectively reducing alcohol-induced oxidative damage. CDPs can significantly increase the abundance of probiotic bacteria and significantly reduce the abundance of harmful bacteria [13]. CD crude polysaccharides (CDCPs) are mainly composed of (1→4)-linked glucans with a small number of pectic polysaccharides. The neuroprotective effect of CDCPs is related to the Nrf2/Keap1 pathway [14]. CDCPs have an obvious antitumor effect. Three purified polysaccharides were obtained from CDCPs, namely CDAP-1, CDAP-2, and CDAP-3 [15]. In vitro experiments have shown that all three polysaccharides can polarize M2 tumor-associated macrophages (TAMs) to the M1 phenotype. As the main component of CDCPs, CDAP-2 can act on M2-type macrophages through the NF-κB signaling pathway mediated by the TLR4 receptor. At present, the research on CDPs mainly focuses on its active functions, but the research on its purification and structure analysis still needs to be further advanced.

3.3 | Iridoids

Iridoid is a monoterpene component with a cyclopentane-pyran ring system among terpenoids, and its parent core is iridoid

alcohol. Its glycoside compounds include catalpol, leuronoside, genipinodic acid, etc. Although the content of iridoid in CD is relatively small, it has a significant effect. It has neuroprotective, antitumor, anti-inflammatory, cholagogue, hypoglycemic, and immunity enhancement effects. Studies have shown that catalpol can stimulate the proliferation of neural stem cells in the subventricular zone, promote their migration to the ischemic cortex and differentiation into neurons or glial cells, enhance the levels of SDF-1α and CXCR4 in the ischemic cortex, and promote neurogenesis and angiogenesis through the SDF-1α/CXCR4 pathway, have neuroprotective effects, and have therapeutic potential for treating cerebral ischemia [16]. Hyperglycemia and lipid metabolism disorders are the main reasons of diabetes. Increasing the degradation of SREBPs is a powerful way to reduce lipids and improve lipid metabolism dysfunction. Leumuride has multiple biological activities, such as antioxidant and anti-inflammatory. It can inhibit SREBP precursors and provide a new direction for the treatment of diabetic nephropathy (DN) [17]. Geniposidic acid can inhibit ovalbumin-induced NF-kB activation and increase the expression of Nrf2, increase the diversity and abundance of the intestinal flora of asthmatic mice, and protect mice from ovalbumin-induced asthma by inhibiting inflammation and regulating the intestinal microbiota [18]. At present, there is little research on the synthetic pathway of iridoid, key enzyme genes, and metabolic regulation of CD. In the future, its structure can be modified and transformed to develop derivatives with stronger biological activity. Through in vivo and in vitro experiments, verify its intervention effect on different disease models.

3.4 | Other Active Ingredients

Other active ingredients of CD, together with PhGs, CDPs, and iridoids, show comprehensive effects in modern medical concerns such as antioxidation, enhancing immunity, delaying aging, preventing cardiovascular diseases, protecting liver and kidney, and regulating endocrine (Figures 1 and 2). The lignans of CD include eudhine A (antibacterial), eugenol (anti-inflammatory), eugenin (inhibiting postprandial blood sugar increase), etc. Guo et al. [19] isolated six lignan glycosides from the stem of CD and found that they can increase the mRNA level of anti-inflammatory cytokines (TGF-β) and play an important role in alleviating the inflammatory response of RAW264.7 cells induced by LPS/IFN-γ. The mechanism involves downregulation of the PI3K/AKT signaling pathway [19]. Bouzayani et al. [20] analyzed it by liquid chromatography-electrospray mass spectrometry (LC-ESI-MS) and found that the content of polyphenols in the aboveground extract of CD was the highest, the content of flavonoids was nearly 3–4 times that of the underground extract, and the content of phenolic acids was very high, showing good antioxidant activity. Hasanov et al. [21] studied and analyzed the macro and trace elements, flavonoids, vitamins, and amino acids in the roots, stems, and flowers of CD. The results showed that the plant was rich in essential elements, including potassium, sodium, calcium, magnesium, and phosphorus. Flavonoids such as apigenin, hypolaetin, hyperazid, and gallic acid were detected in roots, stems, and flowers, while rutin was only found in flowers. Vitamins B_2, B_6, B_9, B_{12}, and PP, as well as vitamin C, were identified in flowers. In addition, there are 20 different amino acids in CD, including serine, cysteine, proline, leucine, glutamine, and asparagine.

4 | Quality Changes and Market Value of CD With Different Maturity

CD is a perennial root-parasitic herb with a unique parasitic method. It lives underground most of the time. It only stretches its spikes out of the ground during the harvest season, blooms, and bears fruit. It only takes more than 30 days from excavation to seed maturity day. The annual harvest seasons are distributed in late spring and late autumn, that is, from early April to late May and from mid-October to the end of November. There are differences in quality between CD in different harvest seasons and different growth years. The maturity of CD directly affects its pharmacodynamic material basis, functional characteristics, quality, market value, and its dynamic component changes have become the focus of research. Existing studies have shown that during the life cycle of CD, its key indicator components show significant spatiotemporal and specific accumulation.

4.1 | Changes in Life Cycle Morphology and Key Index Components at Each Stage of CD

According to the order in which new organs occur on the plant, the life cycle of CD can be divided into parasitic establishment period, elongation period, prebudding period, and reproductive flowering period [4]. During the establishment period of the parasite, CD seeds germinate under the stimulation of the root exudates of the host plant. During germination, germinating tube-like organs are first produced. Under normal circumstances, after the germinating tube stretches to 2–3 mm, the top expands into haustoria. The length of the expanded part is 2.75 mm, and the diameter of the widest part is about 1.19 mm, which is called the primary haustoria [22]. Under the action of enzymes secreted by the primary haustoria and mechanical pressure, they penetrate through the host cortex and further develop into endogenous haustoria in the host. The development of endogenous haustoria marks the establishment of a parasitic relationship, and thereafter the haustoria forms a channel for transporting water and nutrients through the unique parenchyma and the host's vascular bundles [23, 24]. After the host obtains the nutrient source, the haustorium gradually shrinks and falls off together with the seed coat and differentiates into a fleshy stem primordium at the end away from the host root. The fleshy stem primordium is ≥8 mm, and the first spiral leaf primordium appears in the center, which is transformed into elongation [4]. During the long period of fleshy stem elongation, the base of the stem body is thick and thick, gradually thinning upward, and the scale leaves are arranged in a spiral shape, yellowish white. When it stretches to 0–2 cm from the ground surface, it is called the early stage of budding. At this time, the fleshy stem stops growing, and the base continues to grow thicker. The center of the top of the stem bulges to form the inflorescence primordium, with a diameter of 0.8–1.5 cm. It is tightly wrapped by 12–16 yellow–brown bracts, and the outside of the bracts is densely covered with white wool [25]. At the reproductive flowering period, the inflorescences are spike-shaped, spiraling from top to bottom, pale white or lavender. The fleshy stem obviously loses water and shrinks in size, and the pith is hollow, entering the "firewood" stage. The shape of the entire life cycle of CD is shown in Figure 3.

During the entire growth period of CD, hormone levels, mineral content, and active substance accumulation continue to change

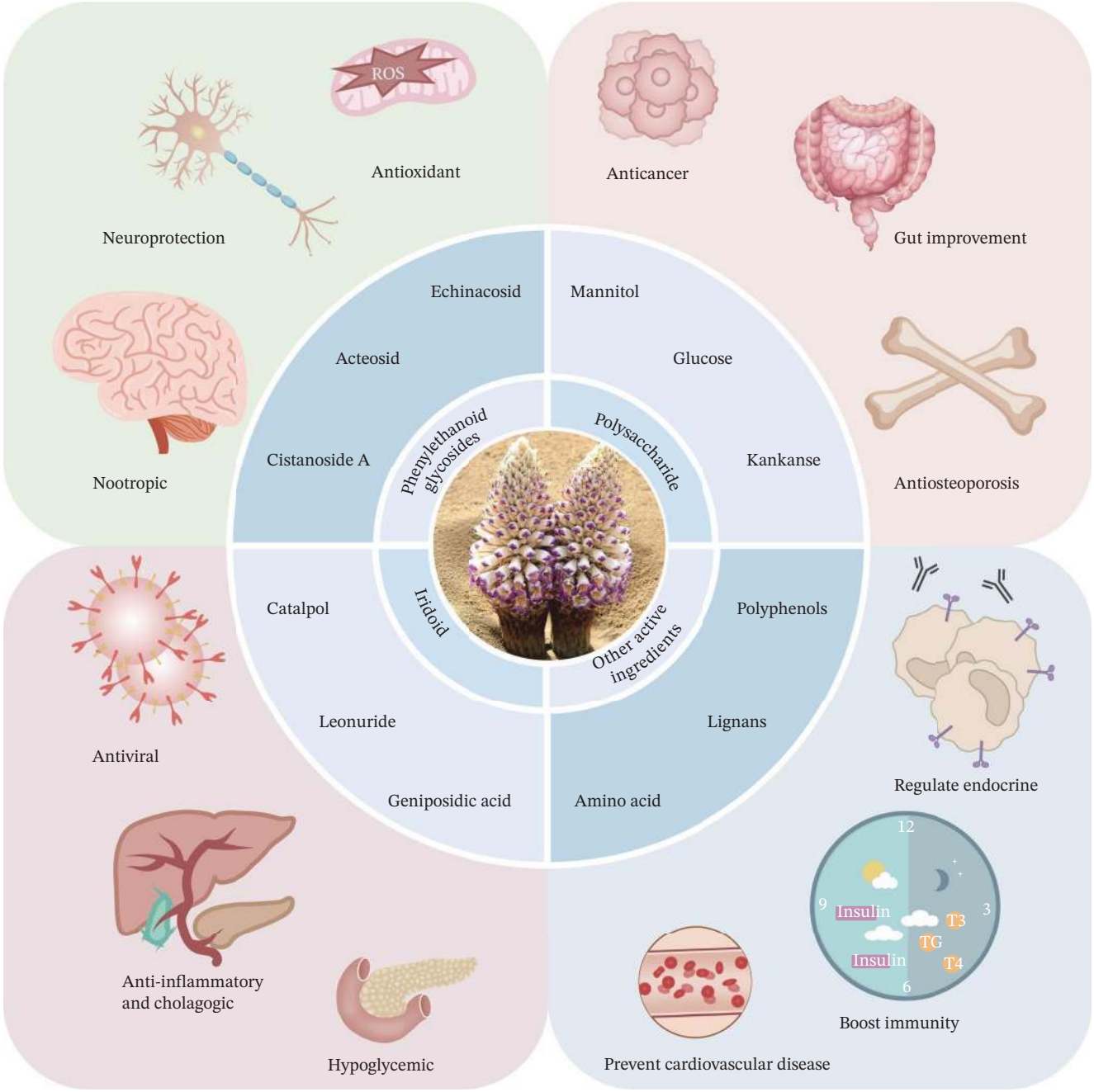


FIGURE 1 | Active constituents and function of CD.

over time (Table 2). Hormones such as indole-3-acetic acid (IAA), zeatin (ZR), gibberellin (GA_3), abscisic acid (ABA), ethylene (ETH), and jasmonic acid (JA) regulate the growth of CD [26, 27]. Different parts of CD have different requirements for mineral elements at different stages, containing macromineral elements such as K, Na, P, Ca, and Mg, and trace mineral elements such as Fe, Zn, Cu, Mn, and B [28, 29]. During the life cycle of CD, mineral elements are the "cofactors" of hormone synthesis and signal transduction. Hormones in turn determine the rate and flow direction of mineral absorption by regulating membrane transport proteins, cell wall relaxation, and gene expression; the two together constitute the "start-up-amplification-turn" three-order coupling mechanism, which ultimately locks the peak window between PhGs and polysaccharides (prebud stage), that is, the "first-class prebud stage maturity." The fluctuations in the content of active ingredients are determined by the three-level linkage of "gene switch-precursor supply-modification of enzyme activity," including the phenylpropane pathway, the tyrosol synthesis pathway, the lignin pathway, and the polysaccharide structure switching pathway, synchronized with the visible signs of maturity [30–32]. Clarifying the dynamic changes of the active ingredients in the whole growth period of CD can provide a theoretical basis for determining the harvesting period for high-yield, efficient, and high-quality CD.

4.2 | Relationship Between Quality and Market Value of CD

The quality grading system for CD has not yet been unified. The existing grading standards are mostly based on morphological

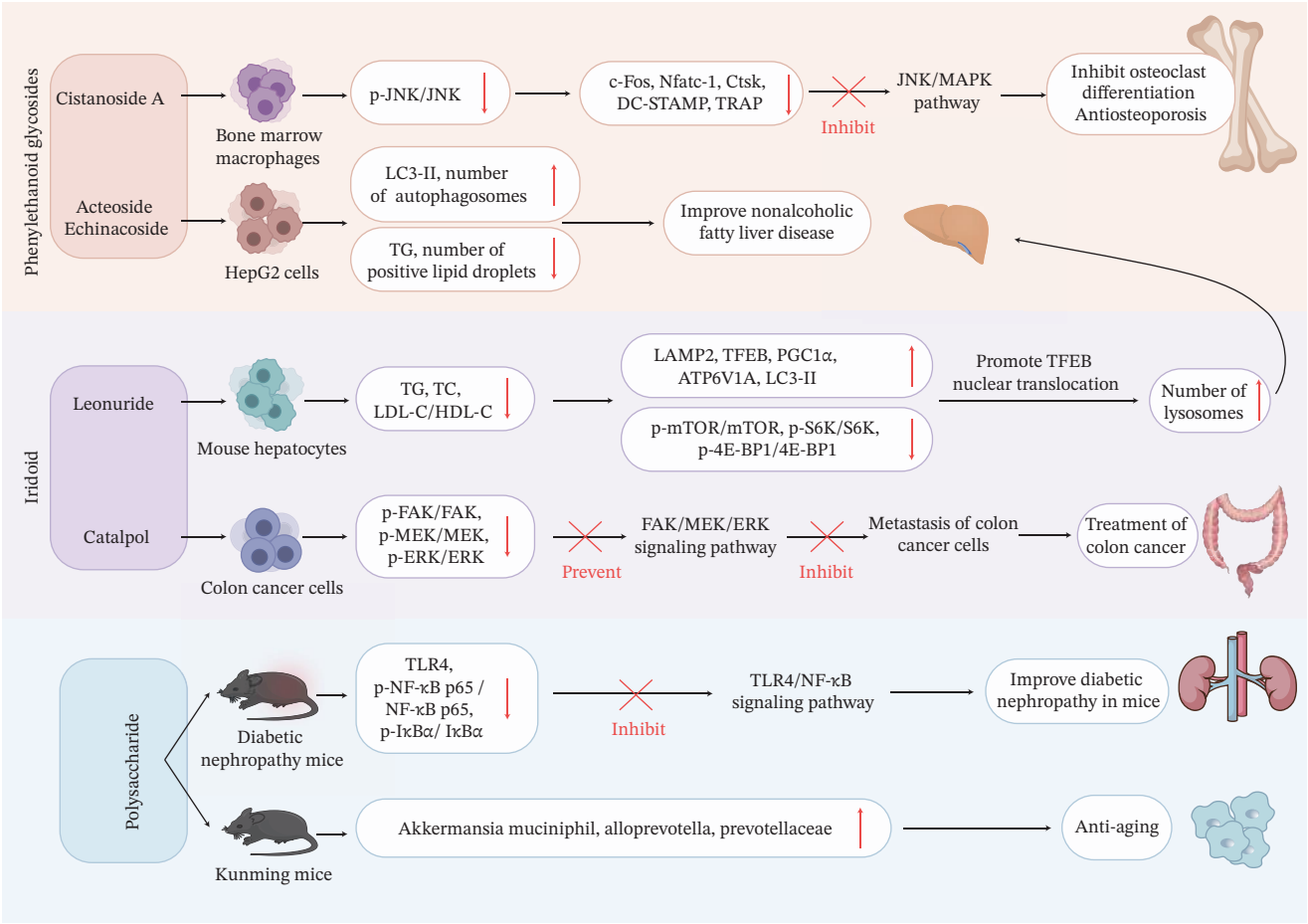


FIGURE 2 | Pharmacological pathway of active constituents in CD.

indicators and are not closely related to the internal components. At present, the classification of CD can be based on its shape, surface characteristics, size, diameter, length, growth period, origin, etc. Generally, the first-class shape is a straight cylinder with a slight bend; the surface is brown or gray–brown, and the fleshy scaly leaves are arranged in a pattern covered by most tiles; the cross-section is brown, with light brown point-like vascular bundles arranged in a wavy ring; the length is greater than 25 cm, and the diameter is greater than 3.5 cm [33]. Li et al. [34] used fingerprint analysis combined with various data statistical methods to build a spectrum-effect relationship and analyzed and screened out genipindic acid, 8-epistrychic acid, echinoside, ACT, isoacteoside, and siphonoside A, which is the antioxidant Q-marker (traditional Chinese medicine quality marker) of CD, providing a reference for the analysis and quality grading of CD.

In recent years, significant progress has been made in the cultivation and industrialization of CD in China, reaching more than RMB 20 billion in 2025, and it is expected that by 2030, the market size of related products is expected to exceed 50 billion yuan. The market price of a special product of cistanche desert in Alxa Desert in Inner Mongolia (average diameter >4 cm, individual mass >500 g, heavyweight, and flexible) is higher than 500 yuan/kg. Wholesale CDs such as Xinjiang wild CD 140 yuan/kg, Qingdao cultivated CD 304 yuan/kg, and imported wild CD 125 yuan/kg. The retail price of desert CD is relatively high, and the price increases with the weight. The price of a whole root weighing 100–500 g ranges from 300 to 1200 yuan/kg. The prices of processed CDs are also different: air-dried or sun-dried is 450 yuan/kg, fresh-dried is 100 yuan/kg, the base part is 1200 yuan/kg, and wine-processed is 600 yuan/kg [35].

5 | Effect of Different Preservation and Storage Methods on the Quality of Fresh CD

At present, the origin of CD is still mainly dry. Although it can be preserved for a long time, it has lost its unique fragrance and crispy and tender taste of fresh products. In recent years, the number of literature reports on postharvest preservation of CD has increased. However, the quality deterioration during postharvest preservation of CD seriously restricts its industrialization development. During the preservation process, the quality of medicinal materials is affected by multiple environmental factors such as air, temperature, humidity, sunlight, microorganisms, and insects. The physical and chemical characteristics of the medicinal materials themselves interact with external environmental factors, resulting in quality degradation and directly threatening the safety and effectiveness of medication use. Modern preservation technology focuses on the synergy of physical, chemical, and biological preservation technologies, combines cold chain transportation, establishes multiple protection mechanisms, extends shelf life, and promotes products to enter a new stage of cross-seasonal, cross-regional, and industrial circulation [7].

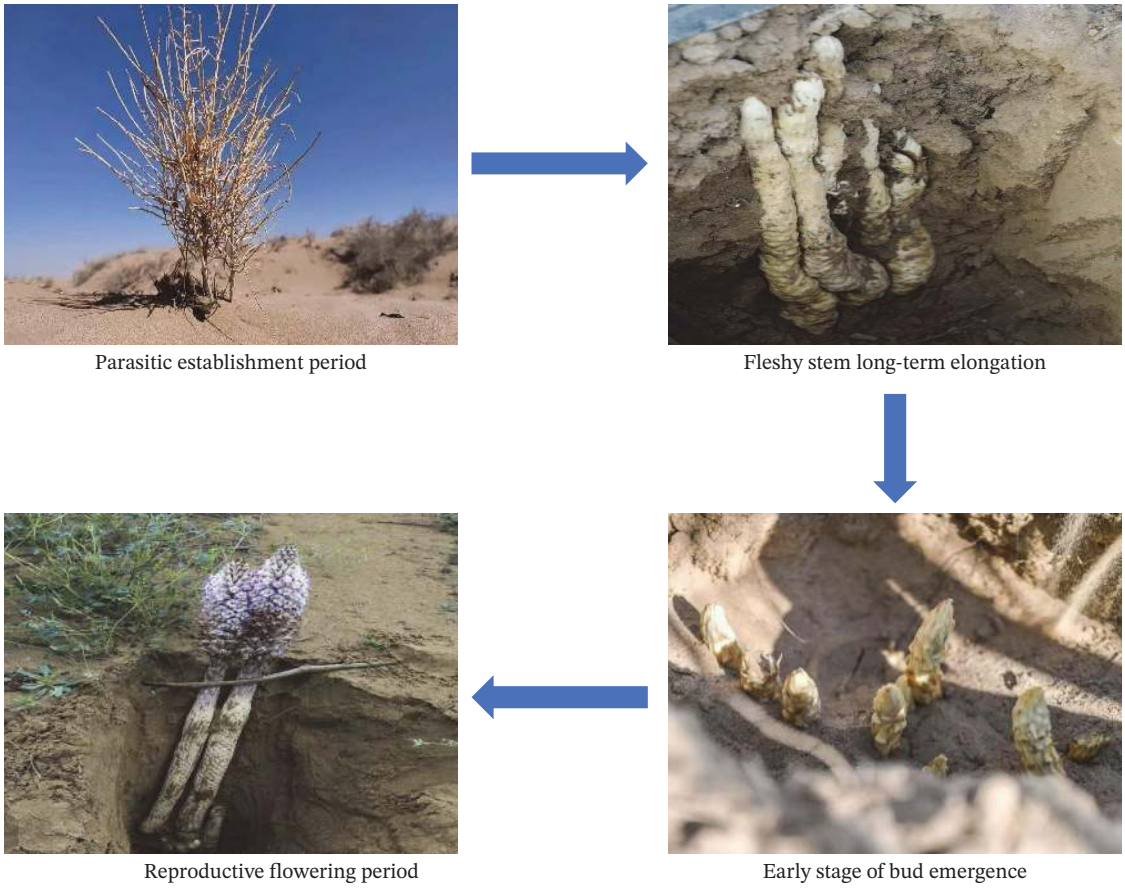


FIGURE 3 | Morphological changes during life cycle of CD.

5.1 | Evaluation Indicators and Reaction Mechanisms for Preservation of Traditional Chinese Medicinal Materials

The preservation effect of fresh Chinese medicinal materials needs to be comprehensively evaluated from multiple dimensions of sensory, physical, chemical, and microbial. Different indicators reflect the changes in different aspects of medicinal materials during the preservation process. Sensory and physical indicators assess appearance characteristics, color, smell, texture/hardness, weight loss, and moisture content/water activity through direct observation or simple measurement. Chemical and composition indicators detect the content of effective ingredients, secondary metabolites, enzyme activities, and nutritional indicators in the medicinal materials. The problems reflected are the degradation or transformation of effective substances and the strength of physiological metabolic activities. Microbial safety indicators include the total number of colonies, mold and yeast counts, and mycotoxins. During the preservation process of fresh medicinal materials, the change in quality is the result of the joint action of internal physiological and biochemical reactions (respiration, enzymatic reactions, and conversion of active ingredients) and external activities (environmental factors and physical factors) (Figure 4).

5.2 | Physical Preservation

Physical preservation mainly suppresses enzyme activity, microbial reproduction, and oxidative hydrolysis reactions by controlling factors such as environmental temperature, relative humidity (RH), and gas composition, thereby extending the storage and preservation period. MAP suppresses breathing by adjusting gas components. Its core lies in gas ratio optimization and temperature and humidity coordinated control. Lu et al. [36] made a modified atmosphere microporous membrane package (6% CO_2 + 4% O_2 + 90% N_2 + 6000-hole microporous membrane), which combined low temperature (4 ± 0.5°C) and high humidity (RH of 90%) to preserve fresh-cut CD for 7 days. Total phenols and flavonoids increased first and then decreased, while total PhGs and CDPs showed a gradually decreasing trend. On the seventh day, the total CDP content was 25.66 ± 0.42 mg DE/g DW, the ECH content was 5.92 ± 0.07 mg/g, and the ACT content was 2.04 ± 0.01 mg/g. The DPPH free radical scavenging rate and ABTS + free radical scavenging rate were generally consistent with the changing trends of total phenol content and flavonoid content, and the FRAP reducing ability showed an overall decreasing trend, which was consistent with the changing trends of VC content and total polysaccharide content [36]. Wei [37] compared the preservation effects of different gas barrier materials (polyethylene [PE], polyamide/PE [PA/PE], polypropylene/butylene adipate terephthalate [PP/PBAT]) on freshly cut CD at a low temperature of 4°C. In contrast, PP/PBAT materials can more effectively extend the retention time of functional components. The reason is that the barrier properties of the materials (water vapor transmission rate [WVTR], carbon dioxide transmission rate [CDTR], and oxygen transmission rate [OTR]) are different. All three are significantly related to the total content of functional components. The slicing process combined with PP/PBAT material can be used for 8 days of preservation. The retention of functional ingredients (ECH, ACT) peaked at

TABLE 2 | Changes in key index components at different stages of the life cycle of CD.

Lifecycle phase	Harvest quality	Mechanism of changes in hormone levels	Mechanism of mineral elements change	Change trend of main active ingredients
1. Parasitic establishment period (haustorial period, 0–3 cm underground)	The lowest medicinal quality and cannot be harvested	Coordinated peak of IAA and ABA; IAA is transported to the polar tip of haustorium, inducing papilla penetration; ABA responds to host rhizosphere drought signals and maintains parasitic pressure	The input rate of N, P, and K is the highest, and the K^+/Na^+ ratio in the aspirator is greater than 6, ensuring osmotic pressure driving; the F^{2+} concentration is 80–120 μg/gDW, providing a cofactor for the phenylpropane pathway in the later period	Key enzyme genes (PAL, C4H, 4CL) of the phenylpropane pathway are only 18%–22% of the elongation period; tyrosol is <0.05 mg/gDW; carbon flow expands to the cell wall and secondary metabolism is inhibited; trace amounts of PhGs (<0.5 mg/gDW), and polysaccharides (<2%) are mainly structural polysaccharides (pectin, hemicellulose)
2. Succulent stems have long extensions (3–15 cm underground, bracts hugging tightly)	In the traditional "sweet big Yun" stage, it can be eaten, but the medicinal grade is third-class	GA_3 and ZR jumped, GA_3 promoted internode cell division and longitudinal expansion; ZR maintained meristematic activity; IAA concentration decreased, and ABA maintained basic level	Ca^{2+} and Mg^{2+} accumulated rapidly (Ca^{2+} increased by 2.5 times), synchronized with cell wall thickening; Fe^{2+} increased to 120–180 μg/gDW, which fluctuated with host root secretion	The expression of PAL, C4H, 4CL, HCT, CYP98A, and UGT85A genes is upregulated by 3–5 times, which is positively correlated with the content of PhGs; the content of tyrosol can increase to 2.1 mg/gDW; the carbon source is sufficient; PhGs entered the linear synthesis stage, with the total amount of echinoside and acteoside 2–6 mg/gDW; the soluble polysaccharide (2%–4%) is mainly composed of glucose–galactose backbone
3. Early stage of budding (0–2 cm from the surface, the bracts begin to loosen)	Best medicinal harvesting window, first-class medicinal materials standard	The second rise in ABA and the sudden increase in ETH induced the tip to shift from "vegetative meristem" to "flower primordium differentiation"; GA_3 decreased by more than 50%, and the stem elongation rate turned to zero	K^+ content reaches the peak during the whole growth period (≥1.2% DW); as an ion cofactor in the phenylpropane pathway, Zn^{2+} ≥35 μg/gDW, is positively correlated with phenylalanine dehydrogenase activity	The expression of HCT, CYP98A, and UGT85A was upregulated by 1.8 times; 4CL no longer increased, preventing carbon and sulfur from leaking to lignin; the content of tyrosol increased to 2.8 mg/gDW; carbon flowed to the top; the synthesis rate of phenylethanoid glycosides reached its peak, with echinoside 4–8 mg/gDW and acteoside 2–4 mg/gDW; at this time, samples were taken 10 cm away from the surface, and the total amount of PhGs was the highest; soluble polysaccharides (4%–6%) appeared in an "active polysaccharide" configuration with increased side chain arabinose
4. Reproductive flowering period (unearthed 2–50 cm)	The quality of medicinal materials has declined, making it only suitable for retaining seeds or extracting polysaccharides	The IAA/ABA ratio inverted again, ETH remained high, accelerating the senescence of flower organs; increase in JA promotes corolla tube elongation and pigment synthesis	N and P were redistributed to inflorescences, and the N content at the base of the stem decreased by more than 30%; Ca^{2+} was heavily deposited on the capsule wall; K^+ in the stem decreased by 25%	The expression of HCT and UGT85A was downregulated by 40%; the expression of lignin pathway CAD and CCR tripled, and the lignin increased by 30%; the total amount of PhGs dropped rapidly by 30%–50%: echinoside dropped to 4 mg/gDW, acteoside dropped to 1.5 mg/gDW; soluble polysaccharides slightly increased to 6%–7%, but the average molecular weight increased from 18 to 45 kDa, and the antioxidant value decreased by 20%

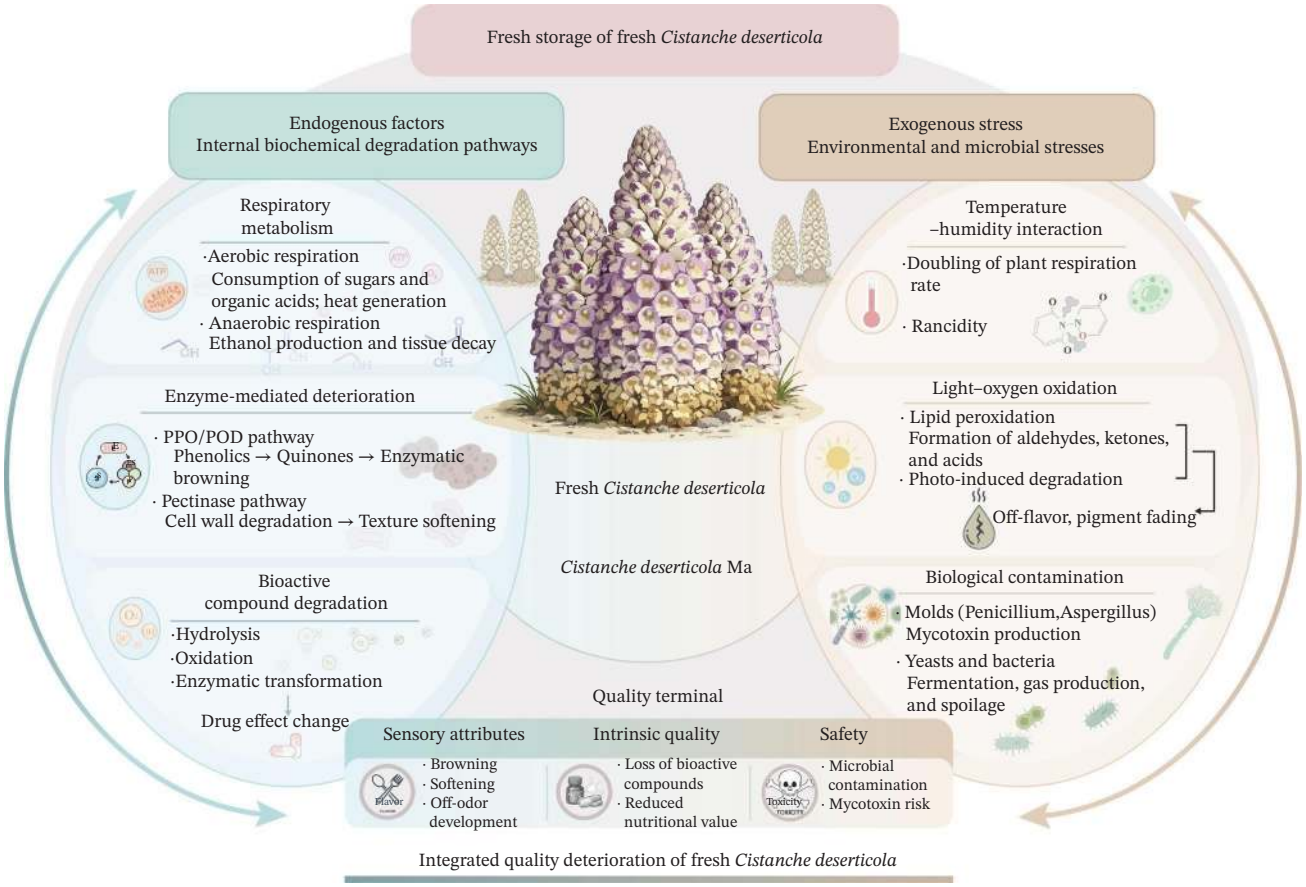


FIGURE 4 | Physiological and biochemical reactions of fresh CD during storage.

609.4 μg/g on the 8th day of storage and dropped to 47.4–244.7 μg/g on the 28th day, which is consistent with Li Qingqing's research results [37, 38]. During preservation and storage, functional components (ECH, ACT) will undergo a dynamic process of briefly increasing first and then continuing to decrease. This dynamic change is directly related to changes in the activities of malondialdehyde (MDA), POD, and PPO in cells, which constitute a "biochemical reaction chain" that leads to the loss of components. Zhang [39] combined two storage temperatures (room temperature 25°C and low temperature 4°C) with three packaging methods (plastic wrap, vacuum pumping, and nitrogen filling) to preserve fresh CD. The appearance indexes (browning, rot, and mildew) of the low-temperature group were significantly better than those of the room temperature group, and the accumulation of membrane lipid peroxidation products (MDA) and the activity of PPO were significantly inhibited. The peak activities of superoxide dismutase (SOD), POD, and catalase (CAT) were delayed, and more active ingredients were retained (the total amount of ECH and ACT was 0.43%) [39]. Liu et al. [40] used four packaging methods: vacuum packaging (VP), oxygen inhalation packaging (OAP), desiccant packaging (DP) and combination packaging (CP) to package dried CD slices in PA/PE composite film bags (OTR: 6.2 cm^3/m^2 d, WVTR: 5.1 g/m^2 d). Comparison found that the degradation rates of CDPs and PhGs in the CP group were the slowest, which may be attributed to the relatively low oxygen and humidity levels in the packaging. The difference is that it belongs to the dry preservation type and must be kept in a low-humidity, low-oxygen, and light-protected environment. It also needs to consider whether the protection of light is protected during storage [40].

At present, other physical preservation technologies have made different progress, such as heat treatment, ultrasound, pulsed electric field, ultraviolet, and nanotechnology. Heat treatment uses hot air, hot water, or steam to treat food to kill or inhibit pathogenic microorganisms and inactivate enzymes that cause quality degradation. Innovative technologies such as catalytic infrared ray (CIR) thermal processing technology have the advantages of uniform heating, high heat transfer efficiency, low energy consumption, and environmental protection [41]. Ultrasound technology uses sound waves with frequencies higher than 20 kHz to inactivate microorganisms and enzymes through mechanisms such as cavitation effects. It is classified as a nonthermal processing technology that avoids damage from heat-sensitive components. Nanocomposites (such as polymer-clay nanosheets, and silver/zinc oxide nanoparticles) delay food spoilage by inhibiting microbial growth and adsorbing oxygen or ETH. For example, packaging materials doped with silver nanoparticles have significant antibacterial effects on *Escherichia coli* and *Staphylococcus aureus*. MAP combines nanosensors to monitor changes in gases in the packaging in real time (such as O_2/CO_2 concentration) and dynamically adjust the preservation environment [42]. These physical techniques are useful for the preservation of CD and require in-depth research in the future.

5.3 | Chemical and Biological Preservation

Food preservatives are essentially food additives with antibacterial or antioxidant functions. They can maintain their fresh appearance while maintaining stable quality. They are an auxiliary

storage method. Preservatives are divided into chemical synthetic preservatives and natural biological preservatives. Although chemical preservatives are effective in preventing the growth of harmful pathogens in foods and extending shelf life, they can also adversely affect consumer health; natural biological preservatives are nontoxic and safe and are suitable for the preservation of food [43].

Wang [44] used three preservatives (methyl jasmonate, 1-methylcyclopropene [1-MCP], and chitosan) in combination with vacuum storage at 4°C for 14 days. Comparing the effects of color, hardness, weight, soluble solids, VC content, and total number of colonies, comprehensive evaluation concluded that 4 μL/L of 1-MCP treatment better delayed the aging and quality degradation of freshly cut CD speed. Metabolites were detected by ultraperformance liquid chromatography–mass spectrometry and metabolic pathways were analyzed. It was found that 1-MCP mainly regulates part of the nucleotide metabolism and amino acid metabolism of freshly cut CD, thereby better maintaining its storage quality [44]. Zhu et al. [45] combined 1.5 g/L cysteine treatment with low-temperature storage of freshly cut CD for 10 days. This treatment has a significant inhibitory effect on PPO activity and effectively delays browning of CD. It can increase the activities of POD, CAT, ascorbate POD (APX) and glutathione (GSH) reductase (GR) of CD and delay the decrease of the content of ascorbic acid (ASA) and reduced GSH, thereby reducing the oxidative damage caused by the accumulation of H_2O_2 and MDA; it can induce the increase of phenylalanine ammonia-lyase (PAL) activity of CD, thereby increasing the accumulation of phenolic substances [45]. His other study was a 1.0 g/L salicylic acid treatment combined with storage of whole fresh CD at 0°C for 60 days. Analysis of cell wall metabolic pathways showed that this treatment effectively inhibited the activities of polygalacturonase, pectinemethylesterase, β- glucosidase, and cellulase, thereby effectively delaying the hydrolysis of protopectin and the accumulation of soluble pectin slows down the softening and browning of CD. Analysis of phenylpropane metabolic pathways showed that this treatment could increase the activities of PAL, cinnamate hydroxylase, and 4-coumaroyl-CoA ligase, promote total phenols, flavonoids, and lignin accumulation, enhance the disease resistance of CD [46]. Song et al. [47] studied the effect of riboflavin-mediated photodynamic technology combined with citric acid on the storage quality of Cistanche deserticola. It was found that it can inhibit enzymatic browning, delay nutrient loss, inhibit microbial growth, enhance antioxidant defense and maintain membrane structural integrity, and effectively maintain the quality of freshly cut Cistanche deserticola [48].

Other preservatives such as methyl jasmonate, sodium alginate, sodium isoascorbate, and citric acid can delay the quality decline of freshly cut cistanche [49, 50]. Natural preservatives have attracted more and more attention due to their high safety, wide application range, and good preservation effect. Other preservatives such as environmentally friendly food preservatives [51, 52] (essential oil and, plant antibacterial polyphenols), lactic acid bacteria, and their metabolites [53] (*Streptococcus lactis* and *Lactobacillus plantarum*) have no research on the preservation of CD. At present, there is little research on natural preservatives on the preservation of CD, which may be because the use of preservatives may have a negative impact on the taste, color and nutritional value of food, causing food to lose its original fresh flavor. In the future, it is necessary to strengthen research on the preservation effect of different preservatives on CD to meet consumers in different regions and expand market demand.

6 | Effect of Different Processing Technologies on the Quality of CD

Innovation in CD processing technology is the core driving force for increasing its added value. Traditional processing methods can retain the active ingredients to a certain extent, but they take a long time, reduce the efficacy quickly, and are limited by seasons and regions, making them suitable for small-scale production. Modern processing technology significantly improves the enrichment of active ingredients by accurately controlling physical and chemical conditions. However, technical complexity and cost investment restrict industrial application. This chapter systematically combs the advantages and disadvantages of traditional and modern processing technologies to provide theoretical support for the optimization of CD processing technology (Table 3).

6.1 | Wine Steaming Technology

Among the traditional processing method systems of CD, steaming and winemaking processes have been verified through hundreds of years of practice and are recognized as the preferred methods that can balance the retention of drug efficacy and the reconciliation of drug properties and can enhance the warming of the kidney effect [67]. Studies have shown that the contents of total CDPs, total PhGs, isoverbesin, and osmanthuside B in CD increased significantly after steaming with wine, while the contents of 2′-acetyl verbesin and verbesin decreased, because steaming with wine may promote hydrolysis, oxidation, enzymatic reaction, and isomerization [68, 69]. Wine-steamed products also promote the conversion of PhGs into more readily absorbed active metabolites (hydroxytyrosol, caffeic acid, and their derivatives). Metabolites may be more easily absorbed into plasma and have better drug effects [70]. After steaming, the number of differential metabolites can reach as many as 47, with 17 upregulated and 30 downregulated, indicating that steaming has a more significant impact on chemical compositions. After steaming, the color of the sample changed from tan to deep black, and the Maillard reaction (reducing sugar reacts with amino acids to form melanoids) was the main cause of blackening. The biosynthesis of phenylpropanoids and flavonoids is significantly enhanced, and some amino acids participate in the Maillard reaction, which is related to the biosynthesis of phenylpropanoid, biosynthesis of flavonoids, and alanine metabolism pathways [71].

The traditional steaming method is “steamer + water pot.” Looking at steam based on experience alone, the timing error is large, and the hardness, color, and active ingredient content of the same batch of medicinal materials fluctuate greatly. The temperature difference between the center and edge and the upper and lower layers of the steamer is large, which is prone to “undercooked” or “oversteamed” carbonization. The quantity is limited and consumes manpower, time, and energy consumption. With the development of science and technology, the emergence of various modern steaming technologies, such as superheated steam technology, pulsed vacuum steaming (PVS), and high humidity hot air impingement steaming (HHAIS), has achieved the advantages of precise temperature control, stable heating,

TABLE 3 | Effects of different processing methods on the active ingredients of CD.

Processing method			Active ingredient			References
			PhGs	CDPs	Iridoids	
Wine steam-processed		Pulsed vacuum steaming pretreatment and hot air impingement drying	The content of ECH and ACT increased by 117.61% and 195.37%, respectively	Content reduced by 26.75%		[54]
		High humidity hot air impingement steaming (HHAIS)	The content is 16.66% when steamed at 95°C and 60% RH for 20 min, the content is 9.35% when steamed at 75°C and 70% RH for 20 min, and the content is 7.56% when steamed at 75°C and 60% RH for 30 min			[55]
		The whole plant was steamed for 20 min and dried at 60°C	The total content of ECH and ACT was 4.34%, which was more than 14 times of the level specified in the pharmacopeia	The content of CDPs was 6%		[56]
		CD was soaked with 30% yellow wine for 4 h and then steamed for 3 h under a pressure of 0.025 MPa	The contents of ECH, ACT, heterococifuside, and 2′-acetyl acteoside were 0.9955%, 0.2859%, 0.9071%, 0.2581%			[57]
Drying technologies	Microwave drying	350 w microwave pretreatment combined with 50°C hot air drying	The contents of ECH and ACT were 80 mg/g and 35 mg/g, respectively			[58]
	Hot air impingement drying	Freeze pretreatment combined with hot air impingement drying	The content of ECH was 154.61 mg/g, and the content of ACT was 46.89 mg/g			[59]
	Pulsed vacuum drying	Temperature 70°C, vacuum to atmospheric pulse ratio of 5:4	The content of ECH was 110.23 mg/g, and the content of ACT was 24.17 mg/g			[60]
		Drying temperature 70°C, pulse ratio 3:4 (vacuum for 3 min/atmospheric pressure for 4 min)	The content of ECH was 100.54 mg/g, and the content of ACT was 35.56 mg/g			[61]
	Ultra-high pressure pretreatment combined with drying	Ultra-high pressure pretreatment combined with hot air drying (296 MPa, 16 min, 81°C) Ultra-high pressure pretreatment combined with freeze drying (295 MPa, 16 min, −40°C)	The retention rates of phenylethanoid glycosides (ECH, ACT, cistanside A and isorbascoside) reached 5.12 mg/g fresh weight and 4.08 mg/g fresh weight, respectively			[41]
	Ultra-high pressure pretreatment combined with radio frequency vacuum drying	250 MPa/20 min	The content of ECH reached 3.09 ± 0.21 mg/g, and the content of ACT was 5.56 ± 0.09 mg/g			[62]
	Far-infrared vacuum drying	The drying temperature is 55°C, the slice thickness is 4 mm, and the irradiation height is 310 mm	The contents of ECH and ACT were 42.24 mg/mL and 46.55 mg/mL, respectively	The content of CDPs was 230 mg/mL	Catalpol (21.4 mg/mL), leonuride (15.4 mg/mL), genipindic acid (242.75 mg/mL)	[63]
	Ultrasonic-assisted vacuum far-infrared drying	Study the effects of radiation temperature (45°C, 55°C, 65°C), ultrasonic frequency (20, 40, 60 kHz), and ultrasonic power (72, 96, 120 W)	At 55°C, 96 W, and 60 kHz, the ACT content (0.67 mg/g) increased 1.9 times compared with natural drying	The highest content (351.58 mg/g) was found at 55°C, 96 W, and 40 kHz	At 55°C, 96 W, and 40 kHz, the content of catalpol (0.56 mg/g) increased by 1.81 times compared with natural drying	[64]

(Continues)

TABLE 3 | (Continued)

Processing method		Active ingredient			References
		PhGs	CDPs	Iridoids	
Freeze drying combined with infrared drying (FD-IR)	FD7.0 h-IR	Compared with a single IRD sample, the retention rate of echinoside in the FD7.0 h-IR sample was 15.41% higher, and the retention rate of verbascoside was significantly 221.21% higher			[65]
Sectional combined drying	Hot air drying is used in the initial stage, and radio frequency vacuum drying is used in the later stage (55°C, vacuum pressure 0.030 MPa, plate spacing 75 mm, sheet thickness 5 mm)	The contents of ECH and ACT were 0.47 mg/mL and 46.55 mg/mL, respectively	275.56 mg/g	The catalpol content is 19.85 mg/mL, and the leonuride content is 20.21 mg/mL.	[66]

continuity, labor saving, energy reduction, safety and cleanliness, and data recording, making the development of steamed products of CD wine more standardized and reducing secondary pollution and energy consumption [72]. Studies have shown that pulse vacuum cooking PVS can significantly increase the PhGs content and hydrolyze polysaccharides into soluble sugar. The soluble sugar content increases (the highest increase is 34.87%) and the polysaccharide content decreases (the highest decrease is 26.75%). Increasing the core temperature of the material to 75°C at the maximum diameter is the best cooking condition, and the PhGs content is 1.11 times higher than that of normal pressure cooking. At this time, the starch completely gelatinizes and forms a barrier layer that adheres to the cell surface that hinders water migration, resulting in a slower drying rate than uncooked samples [54]. Ai et al. [55] investigated the effects of HHAIS parameters on drying characteristics, weight loss, microstructure, color, and active ingredients (PhGs). Temperature, RH, and time are the main factors. Steaming at 95°C, 60% RH for 20 min, 75°C, 70% RH for 20 min, 75°C, 60% RH for 30 min, and then combined with hot air impingement drying (HAID) at 60°C, 6 m/s is the optimal process combination that can simultaneously achieve high PhGs retention (1.02–3.07 times higher than that of the untreated group), low weight loss, and ideal color. The total contents of ACT and ECH were 16.66%, 9.35%, and 7.56%, respectively. After cooking, the color of CD changes from tan to oil black, and the color difference (ΔE) increases with the increase in temperature. The ΔE value is positively correlated with PhGs content ($R^2 \geq 0.84$), and the accumulation degree of PhGs can be quickly predicted by monitoring the ΔE value [55].

6.2 | Drying Technology

Compared with the traditional drying methods (sun drying, air drying, and oven drying), modern drying technologies of Chinese herbal medicines, such as vacuum FD, pulse vacuum technology, short-wave infrared drying (IR), hot air impact drying, and radio frequency vacuum drying, have obvious heat transfer efficiency, energy-saving advantages, and unique environmental protection characteristics. It not only shortens the drying time but also reduces the loss of effective components and improves the quality of medicinal materials.

Li et al. [73] systematically compared the effects of four methods: HAD, IR, FD, and microwave vacuum FD (MFD) on the drying characteristics and quality of CD slices. MFD has the fastest drying rate: it only takes 2.5 h to reach the target water content (<10%), and the time taken is 1/2 of IR, 1/2.2 of HA, and 1/9.6 of FD, respectively. The color is closest to that of fresh samples: the color difference ΔE value is the smallest (10.05), followed by FD (16.4), and HA and IR are severely browned due to long-term oxidation and Maillard reaction (ΔE up to 23.29). MFD quickly forms a surface hardened layer due to microwaves, has the highest hardness and brittleness, and produces a larger pore diameter inside [73]. The presence of enzymes is the main factor affecting the loss of PhGs, followed by high temperature. Microwave treatment (MT) is a good method to inactivate enzymes and ensure quality. The research results of Huang et al. [58] show that compared with steam blanching (STB), hot water blanching (HWB), and MT-700 W, MT-350 W combined with 50°C HAD has the highest retention rate of PhGs. Drying activation energy (E_a):

MT-700 W group has the highest (31.44 kJ/mol), STB group has the lowest (21.11 kJ/mol), indicating that microwave pretreatment requires higher energy consumption. Low-temperature drying at 50°C slowed the thermal decomposition of PhGs, and their half-lives ($t_{1/2}$) were extended to 11.86 h (ECH) and 15.42 h (ACT) in the microwave pretreatment group [58]. Ai et al. [59] systematically investigated the effect mechanism of freezing pretreatment on the efficiency of HAID and product quality of steamed CD (SCD). The results showed that freezing treatment could reduce the secondary damage of SCD during the drying process by shortening the drying time, but a longer freezing time (≥7 days) was not conducive to retaining the content of bioactive ingredients. On the 7th day of freezing, the phenyloside content of SCD increased by 13.90% compared with the untreated sample, the echinoside content was 154.61 mg/g, and the verbascoside content was 46.89 mg/g. The drying time of FT-7 days samples was only 5 h (8 h for the untreated group), the drying time was shortened by 37.5%, and the energy consumption was reduced by 36.64%. FT destroys cell structure through ice crystal growth, increases porosity, softens texture, and promotes the conversion of bound water to free water, thereby accelerating water migration during the drying process. At the same time, the shortened heat exposure time reduces the degradation of heat-sensitive components [59]. Based on the above research, Ai et al. [60] also systematically compared the effects of HAD, HAID, medium and short-wave IR (MSWID) and pulse vacuum drying (PVD) on the drying characteristics and product quality of SCD. Since the vacuum-atmospheric pressure pulse cycle of PVD causes great damage to the cell structure and is conducive to the extraction of effective ingredients, after PVD treatment, the content of ECH (110.23 mg/g) and ACT (24.17 mg/g) is significantly higher than that of other technologies. PVD breaks the balance of water vapor partial pressure through a vacuum-atmospheric pressure pulse cycle, combines infrared heating to improve heat transfer efficiency and accelerate moisture migration. The drying time required is the shortest, only 7 h. Moreover, the water restoration ratio is the highest, which is attributed to the porous structure promoting water penetration [60].

By comparing the drying mechanism, energy consumption, and effects on the appearance, effective components, and stability of different drying methods, it is of great significance to reasonably select drying methods and control process parameters and to ensure the quality, effective component content, and safe storage of medicinal materials. Modern processing technology makes the production process more standardized and controllable. CD is not easy to be contaminated by microorganisms during processing, and the product quality and safety are higher.

7 | Conclusion and Prospect

Harvest maturity is the primary determinant of the chemical integrity of CD. Its essence is to establish a "chemical benchmark" for medicinal materials by regulating the accumulation dynamics of primary and secondary metabolites. This review and analysis show that the effective components of CD show significant temporal and spatial heterogeneity: the early stage of bud emergence is the peak period of PhGs and active polysaccharides, and it is the best harvest point for first-class medicinal materials. Future research needs to combine metabolomic techniques to track the changes in the metabolic flow of CD throughout the growth period and clarify the expression cycle of key genes (PAL, C4H, 4CL, HCT, CYP98A, and UGT85A) in the phenylethanide synthesis pathway, thereby establishing a scientific harvesting window with chemical integrity as the core.

The postharvest stage is a critical transition period for the transformation of CD from an "organism" to a "medicinal material." Its chemical integrity faces triple threats from enzymatic degradation, oxidative stress, and microbial metabolism. Temperature is the core parameter in regulating chemical stability. Low temperature can significantly inhibit PPO and POD activities and delay the oxidative degradation of PhGs. A hypoxic environment reduces the production of reactive oxygen species (ROS) by inhibiting electron transport in the respiratory chain. Preservative agents (such as 1-MCP and chitosan) inhibit respiration and enzyme activity, have antioxidant effects, and can extend shelf life. In the future, it is necessary to establish a related evaluation system of "preservation time-texture properties-drying adaptability" to optimize the entire process of postharvest treatment.

Processing and drying is the "final finalization" of the chemical integrity of CD. The core contradiction lies in the balance between dehydration efficiency and the retention of heat-sensitive components. Steaming processing with wine enhances the kidney, yang, and antioxidant activities of CD by promoting the isomerization of PhGs and increasing the content of polysaccharides. Modern drying technology accurately controls parameters, improves drying efficiency, effectively retains active ingredients, and saves energy. In the future, the potential of emerging technologies such as microwave vacuum drying, heat pump drying, and combined drying (freeze–hot air coupled) should be fully explored. Establish a complete chain of evidence for "drying parameters-microstructure-dissolution characteristics-bioavailability."

To sum up, the quality regulation of CD is a cross-cutting scientific issue involving plant physiology, food chemistry, and engineering thermophysics. This article systematically clarifies the influence of laws and mechanisms of harvest maturity, postharvest preservation, and processing methods on the chemical integrity of CD, laying a foundation for building a theoretical system for quality control throughout the "harves-preservation-processing" chain and providing reference for the formulation of standardized production technical specifications for CD. Future research needs to further integrate multiomics technologies to deeply analyze the molecular mechanisms of component degradation, establish multiobjective optimized process parameter models, and carry out quality evaluation and verification based on biological potency to promote the transformation of the medicinal material industry from experience inheritance to precision manufacturing. Achieve the development goals of controllable quality, efficient resources, and sustainable industry.

Nomenclature

CD:	*Cistanche deserticola* Y. C. Ma
PhGs:	Phenylethanoid glycosides
ECH:	Echinacoside
ACT:	Acteoside

PSD:	Poststroke depression
Tub B:	Tubuloside B
CDPs:	*Cistanche deserticola* polysaccharides
ALD:	Alcoholic liver disease
CDCPs:	*Cistanche deserticola* crude polysaccharides
DN:	Diabetic nephropathy
LC-ESI-MS:	Liquid chromatography-electrospray mass spectrometry
IAA:	Indole-3-acetic acid
ZR:	Zeatin
GA_3:	Gibberellin
ABA:	Abscisic acid
ETH:	Ethylene
JA:	Jasmonic acid
Q-marker:	Traditional Chinese medicine quality marker
PE:	Polyethylene
PA/PE:	Polyamide/polyethylene
PP/PBAT:	Polypropylene/butylene adipate terephthalate
WVTR:	Water vapor transmission rate
CDTR:	Carbon dioxide transmission rate
OTR:	Oxygen transmission rate
MDA:	Malondialdehyde
PPO:	Polyphenol oxidase
POD:	Peroxidase
SOD:	Superoxide dismutase
CAT:	Catalase
VP:	Vacuum packaging
OAP:	Oxygen absorption packaging
DP:	Desiccant packaging
CIR:	Infrared ray thermal processing
MAP:	Modified atmosphere packaging
CP:	Combination packaging
1-MCP:	1-methylcyclopropene
APX:	Ascorbate peroxidase
GR:	Glutathione reductase
ASA:	Ascorbic acid
GSH:	Reduced glutathione
PAL:	Phenylalanine ammonia-lyase
TSS:	Total suspended solids
PVS:	Pulsed vacuum steaming
RH:	Relative humidity
HHAIS:	High humidity hot air impingement steaming
HA:	Hot air drying
IR:	Infrared drying
FD:	Freeze drying
STB:	Steam blanching
HWB:	Hot water blanching
MT:	Microwave treatment
SCD:	Steamed *Cistanche deserticola*
MFD:	Microwave vacuum freeze drying
HAD:	Hot air drying
HAID:	Hot air impingement drying
MSWID:	Medium and short-wave infrared drying
PVD:	Pulsed vacuum drying
ROS:	Reactive oxygen species.

Author Contributions

Yao Zhang and Xiaofeng Liu: writing – original draft, writing – review and editing, conceptualization, funding acquisition, investigation. **Ami Wei**: investigation, methodology, writing – original draft. **Yuanfeng Wu and Luhua Zheng**: investigation, methodology. **Zhaojun Ban**: funding acquisition, resources. **Miroslava Kačániová**: investigation, resources.

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Disclosure

All authors read and approved the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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