Food and Nutrition Sciences, 2026, 17(7), 596-618
https://www.scirp.org/journal/fns
ISSN Online: 2157-9458
ISSN Print: 2157-944X

Research Progress on Chemical Constituents and Pharmacological Activities of Different Parts of *Zanthoxylum bungeanum* Maxim.: A Medicine-Food Homology Plant

Yichen Mu

Chengdu Shude High School, Chengdu, China
Email: muyc9715@163.com

How to cite this paper: Mu, Y.C. (2026) Research Progress on Chemical Constituents and Pharmacological Activities of Different Parts of *Zanthoxylum bungeanum* Maxim.: A Medicine-Food Homology Plant. *Food and Nutrition Sciences*, **17**, 596-618.
https://doi.org/10.4236/fns.2026.177039

Received: May 9, 2026
Accepted: July 17, 2026
Published: July 20, 2026

Abstract

Zanthoxylum bungeanum Maxim. is an important edible and medicinal plant widely used as a spice and traditional medicinal material. Although its pericarp has been extensively investigated because of its characteristic tingling sensation and commercial value, the leaves and seeds remain underutilized despite their distinct phytochemical profiles. This review summarizes the chemical constituents and pharmacological activities of the pericarp, leaves, and seeds, and discusses their implications for part-specific utilization. The pericarp is characterized by alkylamides, especially hydroxy-α-sanshool, and volatile terpenoids, which are closely associated with sensory stimulation, analgesic-like activity, and antibacterial effects. Leaves are enriched in flavonoids and phenolic glycosides such as hyperoside, rutin, quercetin derivatives, and kaempferol derivatives, supporting their antioxidant and preservative potential. Seeds are dominated by unsaturated fatty acids and phytosterols, particularly α-linolenic acid and β-sitosterol, suggesting value as lipid-based nutritional resources. This review aims to provide references for the whole-plant utilization and sustainable development of *Z. bungeanum* as a medicine-food homology plant.

Keywords

Zanthoxylum bungeanum Maxim, Chemical Constituents, Pharmacological Activities, Whole-Plant Utilization

1. Introduction

Zanthoxylum bungeanum Maxim., a deciduous shrub of the family Rutaceae, is widely cultivated in China, particularly in Sichuan, Shaanxi, Gansu, Chongqing, and other southwestern or northwestern regions [1] [2]. Owing to its distinctive pungency, aroma, and tingling sensation, the dried pericarp of *Z. bungeanum* has long been used as an important culinary spice and traditional medicinal material. It has been recorded in the Pharmacopoeia of the People's Republic of China since 1977 and has been used in prescriptions for abdominal pain, toothache, dyspepsia, vomiting, diarrhea, ascariasis, and eczema [1].

As a plant used for both culinary and medicinal purposes, *Z. bungeanum* provides a useful model for examining how plant organs differ in chemical composition, pharmacological function, and industrial value. However, existing studies mainly focus on the pericarp. In contrast, leaves and seeds, although generated in large quantities during cultivation, pruning, harvesting, and processing, are still frequently treated as low-value by-products or agricultural waste.

Different plant organs have distinct physiological functions and metabolic pathways, leading to differences in the accumulation of secondary metabolites and nutritional constituents. In *Z. bungeanum*, the pericarp is generally enriched in alkylamides and aromatic volatile compounds, leaves tend to accumulate flavonoids, phenolic glycosides, and volatile terpenoids, whereas seeds are dominated by lipid-related constituents such as unsaturated fatty acids and phytosterols. These compositional differences are expected to determine organ-specific biological activities and potential uses. Therefore, a systematic comparison of leaves, pericarp, and seeds is essential for clarifying the functional advantages of each plant part.

From the perspective of sustainable development, the comprehensive utilization of *Z. bungeanum* is also of practical significance. Underutilization of leaves and seeds not only reduces the economic value of the crop but may also cause resource waste and environmental pressure when these materials are discarded or burned. Developing part-specific utilization strategies can expand the value chain from a single spice product to functional foods, natural medicinal products, feed additives, cosmetic ingredients, and agricultural by-product valorization.

Accordingly, this review summarizes the chemical constituents and pharmacological activities of different parts of *Z. bungeanum*, with emphasis on the pericarp, leaves, and seeds. The review first compares the distribution of alkylamides, volatile compounds, flavonoids/polyphenols, fatty acids, sterols, and other constituents across plant parts; then discusses how these chemical differences are associated with analgesic, antibacterial, antioxidant, anti-inflammatory, and metabolic regulatory activities; finally, it proposes targeted utilization routes and future research directions for whole-plant resource development.

2. Chemical Constituents of Different Parts of *Zanthoxylum bungeanum*

The chemical constituents of *Z. bungeanum* can be broadly classified into several categories. These include alkylamides, volatile compounds, flavonoids and other polyphenols, fatty acids and sterols, as well as minor constituents such as alkaloids, proteins, polysaccharides, minerals, and pigments. To highlight organ specificity, the chemical composition of the pericarp, leaves, and seeds is discussed separately. Comparable constituent categories are maintained across different plant parts to facilitate systematic comparison.

2.1. Chemical Constituents of the Pericarp

The pericarp is the most intensively studied and commercially utilized part of *Z. bungeanum*. Its chemical profile is characterized by a combination of alkylamides, volatile terpenoids, flavonoids, and coumarins. These constituents jointly determine the typical sensory quality and many of the pharmacological activities of the spice.

2.1.1. Alkylamides (Sanshools)

Alkylamides, often referred to as sanshools, are the primary bioactive and characteristic flavor components found in the pericarp of *Z. bungeanum* [3]. These compounds, specifically polyunsaturated aliphatic acid amides, are the essential substances responsible for the unique "ma" (tingling and numbing) sensation and pungency associated with this spice [4].

Numerous alkylamides have been identified in the *Z. bungeanum* pericarp and can be classified according to structural features [3]. Among these compounds, hydroxy-α-sanshool (HAS) is generally regarded as the most abundant and representative alkylamide, and is therefore considered the principal contributor to the characteristic sensory properties of the pericarp [3]. In addition to HAS, other reported alkylamides include α-sanshool, β-sanshool, hydroxy-β-sanshool, hydroxy-γ-sanshool, as well as a series of structurally related ZP-amides [3]. Although these compounds share similar structural features, they exhibit distinct sensory characteristics. For example, hydroxy-α-sanshool is mainly associated with tingling and numbing sensations, whereas α-sanshool may produce both burning and tingling perceptions, indicating that subtle structural differences among sanshools can significantly influence sensory responses [3] [4].

Moreover, alkylamides in *Z. bungeanum* are chemically unstable and highly sensitive to environmental conditions, which directly affects the quality and bioactivity of the pericarp [3]. In particular, hydroxy-α-sanshool is highly susceptible to ultraviolet irradiation, oxygen exposure, and elevated temperatures, leading to rapid degradation under adverse processing and storage conditions [3]. Consequently, significant losses in tingling intensity and aroma are often observed during long-term storage or high-temperature cooking, reflecting the instability of this key compound [3]. Therefore, beyond serving as characteristic flavor substances, alkylamides, especially HAS, are also regarded as important quality-control markers for *Z. bungeanum* pericarp and its derived products [3].

Furthermore, the distribution of alkylamides within the plant is highly organ-specific. Compared with leaves and seeds, the pericarp is the principal enrichment site of sanshools [3]. This preferential accumulation not only explains why the pericarp exhibits the most pronounced tingling and numbing sensory properties, but also accounts for its role as the primary source of the characteristic analgesic activity of *Z. bungeanum* [3] [4]. Thus, the organ-specific concentration of hydroxy-α-sanshool further highlights its significance as both a phytochemical marker and a functional basis for the pharmacological activities of the pericarp [3].

2.1.2. Terpenoids

The terpenoids of the *Z. bungeanum* pericarp is mainly composed of monoterpenes and oxygenated derivatives, which are key contributors to its characteristic aroma [5]. Among these constituents, linalool, linalyl acetate, and limonene are recognized as the major characteristic components, while other significant compounds such as terpinen-4-ol, myrcene, and 1,8-cineole have also been identified in substantial amounts [6]. The diversity of these volatile compounds contributes to the chemical complexity of the pericarp and underlies its distinctive aromatic profile [5].

Volatile components are the primary determinants of the distinctive odor and flavor of *Z. bungeanum* pericarp [6]. Specifically, these compounds contribute a wide range of sensory notes, including fresh, spicy, floral, citrus, minty, and cooling aromas, which together define the unique sensory experience of the spice [6]. Therefore, the composition and relative abundance of terpenoids are critical factors influencing both the commercial quality and consumer perception of *Z. bungeanum* products [5].

In addition to their sensory importance, terpenoids exhibit distinct physicochemical characteristics. The pericarp is the principal site of terpenoid accumulation, with extraction yields generally reported at approximately 3% - 4% in dried pericarps [6]. However, yields vary considerably depending on sample condition and extraction method, reaching 5.12% or even 8% - 11% when extracted from freshly harvested materials by hydrodistillation [6]. Therefore, these reported yields should not be directly compared, as they were obtained under different sample conditions and extraction methods. This variability highlights the strong influence of processing conditions on terpenoid recovery. The volatile oil is typically described as a light yellowish-green liquid with a density ranging from 0.8563 to 0.947 g/mL, depending on source and extraction conditions [7]. These physicochemical characteristics provide important indicators for evaluating extraction efficiency and product quality.

2.1.3. Polyphenols

The pericarp of *Z. bungeanum* is rich in polyphenolic compounds, among which flavonoids and coumarins constitute major contributors to its non-volatile bioactive profile [8]. These compounds represent an important class of secondary metabolites and contribute substantially to the chemical diversity and biological functionality of the pericarp [8].

Among the flavonoids identified in *Z. bungeanum* pericarp, representative compounds include rutin, hyperoside (hyperin), quercitrin, quercetin, isoquercitrin, and hesperidin [8]. In addition to flavonoids, more than twenty coumarin derivatives have been reported, including simple coumarins such as herniarin, umbelliferone, and scopoletin; furanocoumarins including xanthotoxin, psoralen, marmesin, and imperatorin; as well as pyranocoumarins such as decursinol [9]. This structural diversity suggests that polyphenolic constituents may contribute to multiple biological and physicochemical functions within the pericarp [9].

From the perspective of polarity, these compounds are highly concentrated in the pericarp and are particularly enriched in polar solvent fractions, such as n-butanol and ethyl acetate extracts [10]. This preferential accumulation reflects their relatively high polarity and provides an important basis for selective extraction and fractionation during phytochemical analysis [10].

In addition to their chemical and biological significance, polyphenolic compounds also contribute to important sensory and quality-related traits of *Z. bungeanum* fruits [8]. For example, quercetin has been associated with the green coloration observed in certain varieties, while other flavonoid constituents are involved in regulating the red pigmentation of the pericarp [8]. Therefore, beyond their role as bioactive metabolites, flavonoids and coumarins also serve as important determinants of external appearance and quality differentiation among *Z. bungeanum* cultivars [8].

2.2. Chemical Constituents of the Leaves

2.2.1. Terpenoids

The leaves of *Z. bungeanum* represent an important secondary resource that, although often regarded as an agricultural by-product, contain a rich array of volatile compounds comparable in complexity to those found in the pericarp [5]. This chemical richness highlights their potential for broader utilization beyond conventional cultivation practices [5].

Similar to the pericarp, the terpenoid of *Z. bungeanum* leaves is a complex mixture primarily composed of monoterpenes, sesquiterpenes, and their oxygenated derivatives [5]. Major identified constituents include linalool, d-limonene, sabinene, α-pinene, β-myrcene, and trans-β-ocimene [5]. Moreover, depending on the variety and harvest period, additional compounds such as 1,8-cineole (eucalyptol) and β-phellandrene may also be present, further contributing to the compositional diversity of leaf terpenoids [6]. In some green varieties, linalool can account for nearly 30% of the total volatile profile, indicating its dominant role in defining leaf aroma characteristics [6]. Collectively, these compounds define the fresh aromatic profile of the leaves and provide the chemical basis for both their food applications and biological activities [11].

From a physicochemical and industrial perspective, although the pericarp remains the richest source of terpenoids, with concentrations reaching up to 11% in fresh samples, the leaves still contain abundant aromatic oils suitable for extraction and further utilization [12]. As these values were obtained under different sample conditions and extraction methods, they should not be interpreted as directly comparable. As leaves are frequently discarded during cultivation and harvesting, they are generally regarded as a typical by-product of the *Z. bungeanum* industry [12]. Therefore, the development of efficient strategies for terpenoid extraction from leaves offers considerable potential for sustainable resource utilization [12]. Such approaches could transform agricultural waste into high-value raw materials for the food, cosmetics, and pharmaceutical industries, thereby contributing to both sustainable development and rural economic revitalization [12].

2.2.2. Polyphenols

Polyphenols, especially flavonoids, constitute the primary non-volatile bioactive secondary metabolites in the leaves of *Z. bungeanum* [12]. These compounds are predominantly present as flavonols and their corresponding glycosides, forming the principal basis of the leaf's polyphenolic profile [11]. Compared with the volatile fraction, these non-volatile constituents are particularly important due to their bioactive properties and their contribution to the functional value of leaf extracts [12].

Among the identified flavonoids, hyperoside (quercetin-3-O-galactoside) is recognized as the major bioactive flavonoid specifically enriched in leaf tissue [11]. In addition, rutin (quercetin-3-O-rutinoside) is another prominent flavonoid glycoside widely reported in the leaves [11]. Quercetin and kaempferol serve as the principal aglycone backbones of the leaf polyphenolic system and are commonly accompanied by structurally related derivatives such as quercitrin and kaempferol-3-O-glucoside [11]. This compositional diversity reflects the complexity of leaf polyphenol metabolism and underpins the broad biological potential of leaf-derived extracts [11].

From a physicochemical perspective, leaf flavonoids exhibit relatively high extractability under optimized processing conditions. Under extraction with 80% ethanol at 80˚C, the total flavonoid yield can reach approximately 5.74% [12]. This value reflects a specific extraction protocol and should not be directly compared with yields reported under different experimental conditions. However, these compounds are sensitive to excessive thermal processing, and extraction times exceeding 55 minutes may result in degradation of flavonoid molecular structures [12]. Therefore, careful optimization of extraction parameters is essential to maximize recovery while preserving structural integrity and bioactivity [12].

Notably, the polyphenolic composition of leaves differs markedly from that of the pericarp. Scientific investigations suggest that leaves may contain higher total flavonoid concentrations than fruit pericarps in certain *Z. bungeanum* varieties [8]. In contrast, alkylamides such as sanshools, which define the characteristic "ma" (tingling and numbing) sensation of the pericarp, are present only in extremely low or trace amounts in leaf tissue [11]. This striking compositional difference indicates organ-specific metabolic specialization and explains why the leaves are primarily valued for their flavonoid-mediated bioactivities rather than the sensory pungency characteristic of the pericarp [11].

2.2.3. Minor Alkaloids and Other Compounds

In addition to flavonoids, *Z. bungeanum* leaves contain a variety of minor bioactive secondary metabolites that further enrich their phytochemical complexity and pharmacological potential [13]. Although generally present at lower concentrations than the dominant polyphenolic fraction, these constituents contribute substantially to the functional diversity of leaf extracts [14].

Among these compounds, quinoline alkaloids represent an important specialized class, including skimmianine, dictamnine, and various furoquinoline derivatives [4]. In addition, phenolic compounds such as hyperoside remain characteristic bioactive components within leaf tissue and continue to attract considerable attention due to their pronounced biological activities [11]. Small amounts of alkylamides (sanshools), together with various glycosides and triterpenes, have also been identified; however, these are far less abundant than in the fruit pericarp [13]. This compositional pattern further supports the organ-specific metabolic specialization of *Z. bungeanum* leaves [13].

Functionally, these minor constituents provide an important pharmacological basis for the medicinal value of leaf extracts [14]. For example, leaf-derived hyperoside has demonstrated significant anti-hypoglycemic and hepatocyte-protective effects, suggesting potential applications in the treatment of diabetes-related metabolic disorders [11]. Moreover, certain alkaloids and related extracts have exhibited anti-inflammatory, antibacterial, and anti-tumor activities [14]. Some studies have further reported neuroprotective effects, indicating that specific alkaloids and leaf-derived extracts may alleviate learning and memory impairments [13]. Collectively, these findings suggest that even low-abundance constituents may exert significant biological effects [14].

From a physicochemical perspective, the relative abundance of characteristic tingling alkylamides remains markedly lower in leaves than in the pericarp [13]. This distinction reinforces the functional divergence between these organs, with leaves being primarily characterized by bioactive phenolics and alkaloids rather than sensory-active sanshools [13]. Structurally, these compounds are typically elucidated using advanced spectroscopic techniques, including ^{1}H and ^{13}C nuclear magnetic resonance (NMR), high-resolution electrospray ionization mass spectrometry (HRESIMS), and infrared spectroscopy (IR), and are frequently isolated as amorphous powders or viscous oils [15]. During phytochemical processing, they are generally recovered from polar solvent fractions using methanol, ethanol, or ethyl acetate extraction systems [13]. These analytical and extraction characteristics provide an essential methodological basis for their identification and further functional investigation [15].

2.3. Chemical Constituents of the Seeds

2.3.1. Fatty Acid Composition

The seeds of *Z. bungeanum*, which are generated as a primary by-product during pepper processing, represent an important lipid-rich resource with considerable industrial and nutritional value [16]. Their oil content typically ranges from 27%

to 31% [16]. Because oil contents reported for different crops may be determined using different analytical methods and sample conditions, these values should be interpreted as indicative rather than directly comparable. This high lipid accumulation reflects the seeds' role as the principal energy-storage organ of the plant and highlights their potential for value-added utilization [16].

Chemically, seed oil is primarily composed of fatty acids that can be classified into saturated and unsaturated groups [17]. The fatty acid profile is dominated by four representative components: linoleic acid, oleic acid, palmitic acid, and *α*-linolenic acid [17]. Among these, linoleic acid is one of the most abundant polyunsaturated fatty acids and is recognized as a major resourceful component of the seeds [17]. Oleic acid, as a major monounsaturated fatty acid, contributes to both oxidative stability and nutritional quality, whereas palmitic acid represents the predominant saturated fatty acid fraction [17]. Notably, the seeds are exceptionally rich in *α*-linolenic acid, an essential omega-3 fatty acid, which in some studies has been reported to account for up to 50.94% of total fatty acids [14]. This unusually high abundance distinguishes *Z. bungeanum* seed oil from many conventional edible oils [14].

From a physicochemical perspective, the seed oil is characterized by a high degree of unsaturation, which is a defining feature of its functional and nutritional properties [17]. Unsaturated fatty acids constitute approximately 81.64% of the total fatty acid content in seeds, and this proportion remains high at approximately 78.95% even after refining [17]. This predominance of unsaturated lipids contributes to the oil's liquid state at room temperature and enhances its potential health benefits [17]. Furthermore, the ratio of saturated, monounsaturated, and polyunsaturated fatty acids is approximately 1:2:2.5, indicating a relatively balanced lipid composition [17]. This composition closely aligns with nutritional standards recommended by the World Health Organization, particularly due to the elevated level of *α*-linolenic acid [17].

Compared with other organs of *Z. bungeanum*, the seeds exhibit a distinct metabolic specialization centered on lipid accumulation [17]. For example, the total fatty acid concentration in seeds (331.63 mg/g) is substantially higher than that in the pericarp (108.42 mg/g) [17]. Although both tissues contain fatty acids such as oleic, linoleic, and linolenic acids, the seeds serve as the principal industrial source of these lipids due to their markedly higher oil yield [17]. In contrast to the pericarp and leaves, which are enriched in alkylamides, flavonoids, and other phenolic compounds, seeds generally contain relatively low concentrations of these secondary metabolites, including rutin and hyperoside [17]. This compositional divergence further demonstrates the organ-specific metabolic differentiation of *Z. bungeanum*, with seeds primarily functioning as reservoirs of nutritional lipids rather than sources of sensory-active or pharmacologically dominant secondary metabolites [17].

2.3.2. Phytosterols and Tocopherols

In addition to their abundant fatty acid fraction, *Z. bungeanum* seeds also contain minor unsaponifiable constituents that contribute to their nutritional and pharmacological value [2]. Among these, phytosterols represent an important class of bioactive lipophilic compounds [2].

β-Sitosterol is the most prominent phytosterol identified in *Z. bungeanum* and has been recognized as one of the five major active components highlighted through network pharmacology analyses investigating its medicinal potential [2]. Due to its structural similarity to cholesterol, *β*-sitosterol has attracted considerable attention for its potential physiological activities and therapeutic relevance [2]. Although tocopherols are commonly reported as characteristic minor constituents of many seed oils, the currently available evidence for *Z. bungeanum* seeds primarily emphasizes *β*-sitosterol as the representative sterol component [2].

From a physicochemical perspective, *β*-sitosterol is a plant-derived sterol typically isolated as a white powder from lipophilic extracts using organic solvents such as methanol or dichloromethane [2]. Its sterol-like structure and lipophilic characteristics are consistent with its localization within the seed oil fraction [2]. Although present at much lower concentrations than the dominant fatty acids, phytosterols such as *β*-sitosterol further enhance the functional value of *Z. bungeanum* seed oil and broaden its potential applications in nutritional and medicinal contexts [2].

2.3.3. Other Chemical Constituents

Beyond their dominant lipid fraction, the seeds of *Z. bungeanum* contain a diverse range of additional chemical constituents, further supporting their value as a multifunctional phytochemical resource [16]. This compositional complexity distinguishes seeds not only as an oil source but also as a reservoir of minor metabolites with potential nutritional and pharmacological relevance [2].

Fatty acids remain the predominant chemical constituents of the seeds, with unsaturated fatty acids accounting for up to 78.95% of the total fatty acid profile in seed oil [17]. The principal fatty acids include oleic acid, linoleic acid, and particularly high levels of *α*-linolenic acid, which may exceed 50% of total fatty acids in certain assessments [17]. This exceptionally high degree of unsaturation contributes substantially to the nutritional quality and functional properties of the oil [17].

In addition to fatty acids, the seed coat contains natural melanin, which has recently been identified as a characteristic pigment of *Z. bungeanum* seeds [18]. Seeds are also an important source of essential minerals and proteins, with phosphorus and potassium reported as particularly abundant mineral elements [16]. These nutritional components further enhance the resource value of the seeds and broaden their potential applications in functional food development [16].

Although *Z. bungeanum* seeds do not exhibit the high enrichment of flavonoids characteristic of leaves or the sensory-active alkylamides that define the pericarp, they do contain trace levels of quinoline alkaloids, such as skimmianine, as well as unique unsaturated amides [2]. The presence of these minor secondary metabolites suggests that seed tissue retains a certain degree of phytochemical complexity despite its primary specialization in lipid accumulation [2].

From a physicochemical perspective, the seeds possess markedly higher total fatty acid content (331.63 mg/g) than the pericarp, confirming their role as the principal lipid-storage organ of the plant [17]. These lipids can be efficiently recovered through supercritical CO_2 extraction, which enables the production of relatively pure seed oil while preserving sensitive lipophilic constituents [19]. The extracted oil is typically described as a yellowish liquid enriched with lipophilic secondary metabolites [20]. Collectively, these physicochemical characteristics reinforce the industrial potential of *Z. bungeanum* seeds as a valuable source of edible oil and functional biomaterials [16].

2.4. Comparative Analysis of Chemical Constituents among Different Parts

The distribution of chemical constituents in different parts of *Z. bungeanum* shows clear specialization, which forms the basis for their distinct functional properties (**Figure 1**).

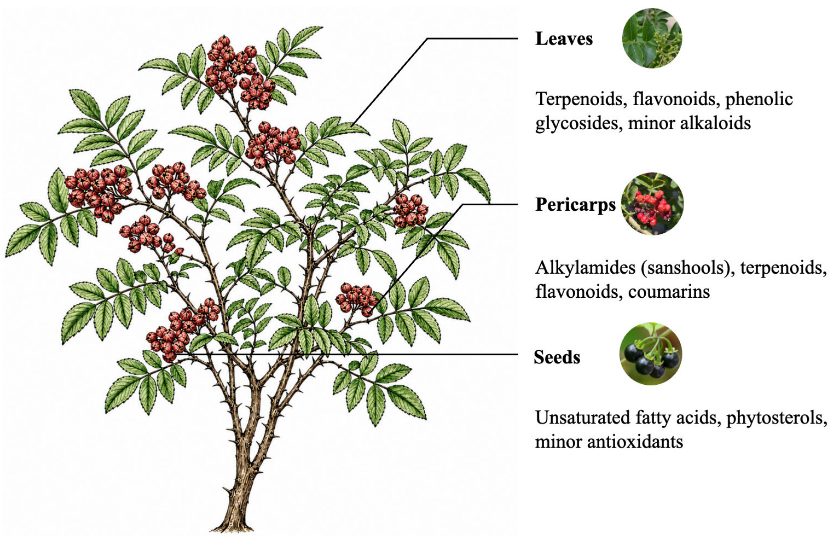

Figure 1. Distribution of major chemical constituents in different parts of *Z. bungeanum.*

Overall, available studies indicate distinct patterns of chemical specialization among different organs of *Z. bungeanum*, although direct quantitative comparisons should be interpreted with caution because constituent contents are often determined using different analytical methods and extraction conditions. The pericarp is characterized by abundant alkylamides and volatile compounds. In contrast, the leaves are relatively richer in polyphenolic compounds such as flavonoids and phenolic glycosides, while containing only trace amounts of alkylamides. The seeds are dominated by lipid components, particularly unsaturated fatty acids and phytosterols, with comparatively lower levels of the characteristic secondary metabolites abundant in the pericarp.

Based on these compositional differences, different plant parts may be preferentially explored for different applications. The pericarp, enriched in alkylamides and volatile compounds, may be suitable for the development of flavoring agents and bioactive extracts. The leaves, characterized by abundant polyphenols, may serve as promising sources of natural antioxidants and functional food ingredients. Likewise, the seeds, rich in unsaturated fatty acids and phytosterols, may represent a promising resource for nutritional oil development and the value-added utilization of processing byproducts.

These observations highlight the importance of part-specific resource utilization and provide a conceptual framework for future studies on the pharmacological activities and potential applications of different *Z. bungeanum* organs.

3. Pharmacological Activities of Different Plant Parts

The pharmacological activities of *Z. bungeanum* are closely associated with its organ-specific phytochemical composition. Due to the differential accumulation of bioactive constituents across the pericarp, leaves, and seeds, each plant part exhibits distinct pharmacological properties and functional applications. This section therefore examines the major biological activities of each organ separately, with emphasis on their underlying chemical basis, experimental evidence, and characteristic functional advantages, followed by a comparative analysis to highlight their complementary pharmacological potential.

3.1. Pharmacological Activities of the Pericarp

3.1.1. Analgesic Effects

Alkylamides (sanshools) are the major contributors to the analgesic and local anesthetic effects of the *Z. bungeanum* pericarp. These compounds, which are polyunsaturated aliphatic acid amides, constitute the characteristic bioactive components of the pericarp [6]. Phytochemical studies have identified more than 50 such compounds within the genus, among which hydroxy-α-sanshool (HAS) is the most abundant and pharmacologically potent constituent in the pericarp [21]. These alkylamides are also responsible for the plant's distinctive "ma" (tingling and numbing) sensation [6].

Experimental studies suggest that the analgesic effects of *Z. bungeanum* are mediated through interactions with sensory receptors and ion channels [6]. Experimental studies indicate that sanshools, particularly HAS, may modulate voltage-gated sodium channels in sensory neurons, where they inhibit the generation and propagation of action potentials, thereby preventing pain signal transmission to the central nervous system [22]. In addition, these compounds modulate Aδ mechanonociceptors, contributing to the alleviation of mechanical pain [22]. They have also been reported to function as agonists of transient receptor potential (TRP) channels, especially TRPV1 and TRPA1, which play key roles in pain perception and thermal sensitivity [23]. From an application perspective, the analgesic properties of the pericarp have long been recognized in Traditional Chinese Medicine (TCM), where it has been used to treat toothache, abdominal pain, and gastrointestinal discomfort associated with "cold" conditions or parasitic infections [6]. Traditionally, practices such as chewing the unripe fruit or bark have been used to provide temporary relief of dental pain, giving rise to its traditional designation as the "toothache tree" [6].

Overall, the pericarp is considered the primary source of rapidly acting alkylamides and therefore represents the plant part most commonly associated with analgesic and numbing effects [6].

3.1.2. Antibacterial Effects

The antibacterial properties of *Z. bungeanum* pericarp are generally attributed to its terpenoids and alkaloids, which together constitute the major contributor for its antibacterial activity [22]. Among these constituents, the essential oil has been the most extensively studied due to its broad-spectrum inhibitory effects against microorganisms, while secondary metabolites such as quinoline alkaloids, including dictamnine and skimmianine, also contribute to the suppression of pathogen growth [24]. This antibacterial activity is closely associated with the characteristic volatile profile of the pericarp, which also serves as an important indicator of its overall quality [5].

Experimental studies have reported that *Z. bungeanum* extracts exhibit potent inhibitory and bactericidal activity against a wide range of common human and foodborne pathogens. In vitro studies have reported ignificant antibacterial effects against Gram-positive bacteria, including Staphylococcus aureus, Bacillus subtilis, and Bacillus anthracis [22]. In addition, strong inhibitory activity has been observed against Gram-negative pathogens such as Escherichia coli, Pseudomonas aeruginosa, Salmonella typhimurium, and Helicobacter pylori [25]. The terpenoid also demonstrates notable antifungal activity, particularly against Candida albicans as well as molds including Aspergillus niger and Penicillium species [22]. This broad antibacterial spectrum highlights the considerable pharmacological and industrial relevance of pericarp-derived extracts.

The terpenoid plays a central role in mediating these antibacterial effects, with major active constituents such as linalool, d-limonene, and terpinen-4-ol serving as the primary functional components [20]. Mechanistic studies suggest that these compounds exert antibacterial activity by disrupting bacterial cell wall and membrane integrity, thereby increasing membrane permeability and compromising cellular homeostasis [26]. For example, *in vitro* studies have shown that linalool can damage the membrane structure of E. coli, resulting in leakage of intracellular contents, depletion of adenosine triphosphate (ATP), and eventual cell death [27]. Furthermore, terpenoid components can inhibit microbial biofilm formation, as demonstrated in studies involving Candida albicans, thereby enhancing their effectiveness against persistent microbial colonization [26].

Traditionally, these antibacterial effects have supported the medicinal use of *Z. bungeanum* in the treatment of diarrhea, skin infections, and dental diseases [25]. More recently, its reported antibacterial activity has attracted increasing attention in the development of natural food preservatives, antibacterial packaging materials, and anti-pruritic skincare products [5]. Overall, this terpenoid-centered aantibacterial profile complements the pericarp's rapid analgesic effects mediated by alkylamides [7]. Overall, available evidence suggests that the pericarp is primarily associated with rapid sensory responses and antibacterial activity, whereas the leaves and seeds have been investigated more extensively for antioxidant and metabolic-related properties, respectively.

3.2. Pharmacological Activities of the Leaves

3.2.1. Antioxidant Activity

Experimental studies have shown that Z. *bungeanum* leaf extracts exhibit significant antioxidant activity, which is primarily attributed to their high concentrations of flavonoids and phenolic compounds [11]. These polyphenolic constituents form the major contributor for the antioxidant potential of leaf tissue. Among them, hyperoside (quercetin-3-O-galactoside) has been identified as a major bioactive compound and a potent natural antioxidant specifically enriched in the leaves [11]. Other important contributors include rutin, quercetin, and kaempferol, which collectively provide the leaves with strong radical-scavenging capability through their polyhydroxylated structures [11].

The antioxidant activity of *Z. bungeanum* leaf extracts has been extensively evaluated using standardized *in vitro* assays. In DPPH (1,1-diphenyl-2-picrylhydrazyl) radical-scavenging assays, leaf extracts demonstrate strong concentration-dependent antioxidant activity, reflecting the high abundance of phenolic compounds capable of neutralizing free radicals [11] [15]. Their total antioxidant capacity has also been validated using ABTS (2,2'-azino-bis-3-ethylbenzothiazoline-6-sulfonic acid) assays, in which leaf flavonoids effectively reduce ABTS radicals and significantly contribute to the overall Total Antioxidant Capacity (T-AOC) of the plant [12]. Furthermore, strong performance has been observed in FRAP (Ferric Ion Reducing Antioxidant Power) and hydroxyl radical-scavenging assays, with antioxidant activity increasing proportionally with extract concentration [15] [12]. These findings collectively demonstrate strong free radical-scavenging activity *in vitro*.

Comparative evaluations further highlight the potency of this antioxidant activity. In several studies, *Z. bungeanum* leaf extracts exhibited antioxidant performance superior to the synthetic antioxidant butylated hydroxytoluene (BHT), although generally lower than that of high-purity vitamin C [12]. For example, at a concentration of 10 mg/L, leaf extracts achieved approximately 15.94% of the antioxidant activity of vitamin C while substantially exceeding the performance of BHT [12]. Such results demonstrate the considerable practical value of leaf polyphenols as naturally derived antioxidant agents.

The biological significance of this antioxidant profile is reflected in the demonstrated pharmacological effects of leaf-derived compounds. In experimental models, hyperoside, for example, has been reported to exhibit hepatocyte-protective activity and alleviate hyperglycemia-induced oxidative stress in diabetic models

[11]. In addition, the strong capacity of leaf extracts to inhibit lipid oxidation has led to growing interest in their application as natural food preservatives, such as in fresh-cut fruit and processed aquatic products, as well as high-value raw materials for the cosmetics and pharmaceutical industries [12].

Overall, available evidence suggests that the antioxidant activity of *Z. bungeanum* leaves is largely associated with their abundant polyphenolic compounds. This functional specialization highlights the leaves as an important resource for sustainable medicinal exploitation and industrial development, highlighting their potential for antioxidant-related applications.

3.2.2. Antibacterial Activity

The antibacterial activity of *Z. bungeanum* leaves is generally attributed to their abundant flavonoids, polyphenols, and terpenoid, which together constitute the principal material basis for pathogen inhibition [12]. Unlike the pericarp, which is mainly characterized by sensory-active alkylamides, the leaves represent a typical by-product enriched in aromatic oils, particularly linalool and other terpene derivatives, as well as non-volatile polyphenolic compounds that provide broad-spectrum antibacterial potential [12]. This compositional profile underpins the unique functional specialization of leaf tissue in microbial inhibition and environmental defense.

In vitro studies have reported antibacterial activity of leaf extracts and terpenoids exhibit inhibitory effects against a wide range of biological threats. Significant antibacterial activity has been reported against common foodborne and pathogenic bacteria, including Escherichia coli and Staphylococcus aureus [25]. This antibacterial efficacy is concentration-dependent and has been closely associated with the abundance of linalool and related terpene constituents within the leaf volatile profile [25]. In addition to bacterial inhibition, leaf-derived flavonoids exhibit pronounced allelopathic activity against bloom-forming freshwater algae such as Microcystis aeruginosa, suggesting considerable ecological application potential [12]. Furthermore, these antibacterial properties may partly explain the traditional use of leaf extracts in addressing skin, oral, and gastrointestinal microbial disorders, including diarrhea and dysentery [25].

The antibacterial mechanisms of leaf-derived compounds involve multiple modes of physiological disruption. Volatile components such as linalool compromise microbial cell wall and membrane integrity, increasing permeability and causing leakage of intracellular contents that ultimately leads to cell death [24]. In algae, concentrated leaf extracts interfere with the oxygen-evolving complex at the donor side of photosystem II (PSII) and inhibit electron transport processes, thereby effectively suppressing photosynthetic activity and controlling algal proliferation [12]. This dual capacity for direct microbial inhibition and photosynthetic interference distinguishes leaf extracts from the primarily sensory-defense mechanisms observed in the pericarp.

From an industrial perspective, the synergistic antibacterial and antioxidant properties of *Z. bungeanum* leaves make them promising candidates for the development of natural preservatives and environmentally friendly bioactive agents [12]. For example, leaf extracts and powders have been reported to significantly extend the shelf life of fresh-cut apple slices [25]. In processed aquatic products such as salted silver carp, leaf-derived additives not only inhibit lipid oxidation and microbial growth but also improve sensory attributes including color and flavor [25]. Moreover, their strong activity against algae and pathogenic microorganisms positions them as eco-friendly alternatives to synthetic preservatives for applications in food preservation, cosmetics, and environmental restoration [12].

Overall, the leaves exhibit a distinctive functional profile centered on broad-spectrum antibacterial and allelopathic activity. Compared with the pericarp, which specializes in rapid analgesic and antibacterial defense, and the seeds, which are primarily associated with nutritional and metabolic regulation, current evidence suggests that the leaves possess promising antibacterial and allelopathic properties, particularly in food preservation and related applications. These predictions suggest a potential role as an underutilized resource for sustainable industrial development.

3.3. Pharmacological Activities of the Seeds

3.3.1. Antioxidant Activity

Available evidence suggests that the antioxidant activity of *Z. bungeanum* seed extracts and seed oil is primarily associated with their abundant unsaturated fatty acids and lipid-soluble antioxidant constituents, which together constitute the principal material basis for oxidative protection [28]. As a major lipid-rich by-product, the seeds possess a distinct antioxidant profile that differs fundamentally from the polyphenol-dominated antioxidant mechanisms of the leaves. The antioxidant potential of seed oil is closely linked to its high degree of unsaturation, with unsaturated fatty acids accounting for approximately 78.95% to 81.64% of total fatty acids [28]. Among these, α-linolenic acid is particularly abundant, reaching up to 50.94% in certain analyses, alongside substantial levels of linoleic acid and oleic acid [28]. In addition, lipid-soluble antioxidants such as tocopherols and β-sitosterol further enhance the oxidative stability and medicinal value of seed oil [28]. The seed coat also contains natural melanin, a phenolic pigment with notable antioxidant activity that represents an additional functional resource [29].

The antioxidant activity of seed extracts has been evaluated using several *in vitro* assays. In DPPH radical-scavenging assays, seed extracts exhibit substantial free radical-neutralizing capacity, with extraction solvent selection significantly influencing antioxidant performance [28]. Extracts prepared with 90% ethanol and methanol have shown particularly strong scavenging activity, which correlates closely with the phenolic content retained in the seed residue [28]. Similarly, FRAP assays indicate that antioxidant reducing power reaches maximal levels when extraction is performed with 50% ethanol, suggesting an important contribution from flavonoid and phenolic constituents present in the by-product matrix [28]. Furthermore, the high abundance of α-linolenic acid and other polyunsaturated fatty acids may contribute to the inhibition of lipid peroxidation, thereby protecting both food systems and biological membranes from oxidative deterioration [28].

The biological significance of this antioxidant profile is reflected in the demonstrated metabolic and cardiovascular benefits of seed-derived products. Animal studies have shown that seed oil can alleviate high-fat diet-induced hyperlipidemia by significantly reducing serum triglyceride (TG), total cholesterol (TC), and malondialdehyde (MDA) levels, while improving oxidative stress status through activation of the PPAR-γ signaling pathway [6]. In addition, the characteristic combination of α-linolenic and linoleic acids has been reported to prolong bleeding and clotting times in mice, suggesting anti-thrombotic potential possibly mediated through regulation of the PI3K/Akt pathway and reduced vascular oxidative injury [6]. These findings indicate that the antioxidant activity of seed oil is closely linked to its broader metabolic regulatory functions.

From an industrial perspective, the strong antioxidant properties of *Z. bungeanum* seeds support their development as high-value edible oils and natural antioxidant resources for food and pharmaceutical applications [28]. This potential is particularly significant given that the seeds are often treated as low-value byproducts during conventional pepper processing. Their conversion into functional antioxidant products offers an effective pathway for improving resource utilization and promoting sustainable industrial development.

Overall, the antioxidant profile of *Z. bungeanum* seeds, centered on lipid-based radical scavenging and oxidative stability, provides a clear functional contrast to the pericarp, which specializes in rapid sensory-defense activities, and the leaves, which rely primarily on flavonoid-mediated antioxidant protection. Overall, current evidence suggests that seeds represent a promising resource for nutritional and metabolic applications.

3.3.2. Nutritional and Metabolic Regulation Potential

The metabolic regulatory potential of *Z. bungeanum* seeds is generally attributed to their exceptionally high content of essential unsaturated fatty acids and bioactive sterols, which together constitute the principal material basis for their nutritional and therapeutic functions [17]. As a major lipid-rich by-product of pepper processing, the seeds possess a distinct biochemical profile dominated by α-linolenic acid, linoleic acid, and oleic acid, with α-linolenic acid accounting for up to 50.94% of total seed oil in some analyses [17]. In addition to these essential fatty acids, β-sitosterol has been identified as a representative bioactive sterol within the seed fraction. Owing to its relatively high oral bioavailability and cholesterol-like structure, this compound is considered an important contributor to the seeds' metabolic regulatory effects [2].

Experimental animal studies have suggested that the seeds' demonstrated capacity for metabolic regulation, particularly in lipid and glucose homeostasis. Experimental studies have shown that administration of seed oil significantly reduces serum total cholesterol (TC), triglycerides (TG), and malondialdehyde (MDA) levels in hyperlipidemic models, indicating pronounced hypolipidemic and antioxidative effects [15]. These benefits are thought to be mediated through activation of the peroxisome proliferator-activated receptor gamma (PPAR-γ) pathway, which improves oxidative stress markers and promotes restoration of lipid balance [15]. These findings indicate the potential of seed oil for further investigation in lipid metabolism regulation.

In addition to lipid regulation, *Z. bungeanum* seeds also exhibit promising anti-diabetic effects. Network pharmacology and molecular docking analyses indicate that β-sitosterol may function as a key anti-diabetic constituent by interacting with insulin-related molecular targets [2]. These findings provide a theoretical basis for further experimental validation but do not by themselves confirm anti-diabetic efficacy.

Furthermore, the characteristic combination of α-linolenic and linoleic acids confers anti-thrombotic potential. Experimental observations indicate that these fatty acids have been reported to prolong bleeding and clotting times, likely through attenuation of oxidative vascular damage and regulation of the PI3K/Akt signaling pathway [15]. This vascular-protective effect complements the seeds' broader metabolic benefits and highlights their potential role in cardiovascular health management.

Overall, available evidence suggests that the seeds exhibit a functional profile primarily associated with lipid metabolism and vascular health-related activities. Compared with the pericarp, which has been more extensively investigated for its analgesic and antibacterial properties, and the leaves, which are mainly characterized by polyphenol-related antioxidant activity, the seeds have attracted increasing attention for their nutritional composition and potential metabolic benefits. Although current findings from experimental studies and network pharmacology analyses indicate promising applications of seed-derived products, further in vivo investigations and clinical studies are still required to validate their efficacy and underlying mechanisms. The utilization of *Z. bungeanum* seeds as edible oils and other value-added products therefore represents a promising direction for future research and sustainable resource utilization.

3.4. Comparative Analysis of Pharmacological Activities

The pericarp, leaves, and seeds of *Z. bungeanum* exhibit marked organ-specific differences in chemical composition, resulting in distinct yet complementary pharmacological activities. Although previous studies have predominantly focused on the medicinal and culinary applications of the pericarp, comparative evidence suggests that the leaves and seeds also possess distinct functional characteristics and potential applications [7]. As summarized in **Table 1**, these three plant parts differ substantially in their dominant bioactive constituents, relative pharmacological emphasis, and pharmacological specificity, collectively forming the biochemical foundation for the whole-plant utilization of *Z. bungeanum*. The ratings are intended to summarize the relative emphasis of currently available evidence rather than absolute pharmacological efficacy.

Table 1. Semi-quantitative comparison of the dominant pharmacological characteristics of different organs of *Z. bungeanum.*

Plant Part	Dominant Constituents	Major Pharmacological Activities	Relative Activity Level*	Functional Orientation
Pericarp	Alkylamides (HAS), terpenoids	Analgesic, local anesthetic, antibacterial	★★★★★	Rapid-response sensory and antimicrobial defense
Leaves	Hyperoside, flavonoids, terpenoids	Antioxidant, antibacterial, hepatoprotective	★★★★☆	Preventive protection and oxidative stress regulation
Seeds	Unsaturated fatty acids, β-sitosterol	Antioxidant, hypolipidemic, anti-diabetic, anti-thrombotic	★★★★☆	Long-term metabolic regulation and nutritional support

*Activity intensity ratings are semi-quantitative assessments intended for comparative discussion only. The ratings are based on the relative abundance of dominant bioactive constituents, the consistency of currently available experimental evidence (including *in vitro* and animal studies), and the extent to which each pharmacological activity has been reported in the literature. They are not derived from standardized efficacy measurements and should not be interpreted as direct quantitative comparisons among different plant parts.

4. Challenges and Future Perspectives

4.1. Current Utilization Patterns

The current industrial utilization of *Z. bungeanum* is highly concentrated on the pericarp, reflecting its dominant economic and commercial importance. As one of China's most important traditional condiments, *Z. bungeanum* is primarily valued for its edible and medicinal pericarp, which contains the characteristic pungent compounds and multiple bioactive constituents that have attracted widespread attention in both culinary and pharmaceutical applications [5] [8]. The annual production of Chinese *Z. bungeanum* has been reported to exceed 450 thousand tons, with a market value reaching approximately US$18 billion, demonstrating the substantial scale of the pericarp-centered industry [8]. At present, however, more than 90% of the pericarp is still marketed in whole-peppercorn or bulk pericarp form, indicating that processing remains largely limited to primary commercialization with relatively low levels of deep-value-added product development [18].

In contrast, the leaves, seeds, and other byproducts generated during cultivation and processing remain significantly underutilized despite their demonstrated phytochemical and functional potential [17]. Current research and industrial development have largely focused on mature pericarps, while systematic exploitation of other plant parts, particularly seeds and seed oil, remains comparatively limited [17]. Large quantities of agricultural residues, including seeds, leaves, and stems, are often discarded or burned during harvesting and processing, resulting not only in substantial resource waste but also in environmental concerns [25]. Notably, seeds account for approximately 60% of the total fruit mass as a major processing byproduct. Although a small proportion is used for seedling propagation or oil extraction, the majority is still discarded or used as low-value fertilizer [18]. Consequently, the current resource utilization rate of *Z. bungeanum* byproducts remains relatively low, and the associated industrial chain is still characterized by simple processing methods, limited product diversification, and low added value [25].

This imbalance between intensive pericarp utilization and the neglect of other bioactive plant parts highlights a critical opportunity for sustainable industrial transformation. Improving the comprehensive utilization of *Z. bungeanum* resources through the development of high-value products derived from leaves, seeds, and processing residues might be essential for enhancing economic efficiency, reducing environmental burden, and promoting the long-term sustainable development of the industry.

4.2. Future Research Directions

Although substantial progress has been made in elucidating the chemical composition and pharmacological activities of *Z. bungeanum*, current research remains largely focused on the pericarp, while the leaves, seeds, and other byproducts remain comparatively underexplored [8] [17]. Given the clear organ-specific differences in bioactive constituents and functional specialization, future studies should move beyond the traditional pericarp-centered framework toward a more integrated whole-plant utilization strategy.

First, systematic comparative studies across different plant parts should be strengthened. Although major classes of compounds have been identified in the pericarp, leaves, and seeds, their dynamic accumulation patterns, spatial distribution, and interactions under different developmental stages and cultivation conditions remain insufficiently understood [8]. The integration of comparative metabolomics and transcriptomics would provide deeper insight into the biosynthetic mechanisms underlying organ-specific accumulation of alkylamides, flavonoids, and fatty acids, thereby supporting selective breeding and optimized cultivation practices.

Second, further investigation into molecular mechanisms is needed to clarify the pharmacological basis of *Z. bungeanum*. Current studies have identified several potential pathways involved in analgesic, antioxidant, and metabolic regulatory effects, including TRP channel modulation, PI3K/Akt signaling, and PPAR-related pathways [2] [23]. However, many of these findings remain preliminary. Future research should emphasize target validation, receptor-binding studies, and *in vivo* mechanistic experiments to establish clearer structure-activity relationships and reveal potential synergistic effects among multiple constituents.

Third, the establishment of standardized quality evaluation systems for different plant-derived products is urgently required. Current quality assessment is still largely based on sensory indicators such as aroma intensity and pungency, particularly for commercial pericarp products [5]. Future efforts should focus on identifying representative chemical markers for different plant parts, such as hydroxy-α-sanshool for the pericarp, hyperoside for leaves, and α-linolenic acid for seeds, combined with chromatographic fingerprinting and bioactivity-based evaluation methods.

Finally, future development should prioritize comprehensive industrial utilization and green processing technologies. Advanced extraction methods, including supercritical CO_2 extraction and ultrasound-assisted extraction, offer promising approaches for improving extraction efficiency while reducing environmental impact [18]. At the same time, integrated utilization strategies combining pericarp processing, leaf extraction, and seed oil refinement should be developed to maximize resource efficiency and promote sustainable industrial transformation [25].

Overall, future research should emphasize systematic comparative investigation, mechanistic clarification, quality standardization, and integrated utilization. Such efforts will provide the scientific foundation for transforming *Z. bungeanum* from a traditionally pericarp-centered crop into a fully valorized medicinal and industrial resource.

5. Conclusions

As a representative medicine-food homology plant, *Zanthoxylum bungeanum* Maxim. possesses remarkable phytochemical diversity and organ-specific functional specialization, which together underpin its long-standing dual application in traditional cuisine and medicinal practice. This review systematically summarizes recent research progress on the chemical constituents and pharmacological activities of different plant parts, highlighting the organ-specific distribution of major bioactive compounds and their associated pharmacological activities.

The pericarp remains the most extensively studied and industrially utilized component, owing to its high enrichment of alkylamides and terpenoids, particularly hydroxy-α-sanshool and characteristic terpenoid compounds. These constituents are considered to contribute to rapid sensory stimulation, local anesthetic effects, and potent antibacterial activity, establishing the pericarp as the primary functional tissue for acute pharmacological intervention and culinary applications. In contrast, the leaves are characterized by abundant flavonoids and polyphenolic compounds, such as hyperoside, rutin, and quercetin derivatives, which provide strong antioxidant, antibacterial, and hepatoprotective properties. These features position the leaves as an important resource for preventive health regulation and natural preservative development. Meanwhile, the seeds exhibit a distinct chemical profile dominated by unsaturated fatty acids and bioactive sterols, particularly α-linolenic acid and β-sitosterol, which contribute to antioxidant protection, lipid metabolism regulation, anti-diabetic potential, and cardiovascular benefits. These findings suggest that the seeds have considerable potential for long-term nutritional intervention and metabolic health management.

These pronounced differences in chemical composition reflect a highly organized pattern of functional specialization among plant organs. More importantly, the pharmacological activities of the pericarp, leaves, and seeds are not redundant but strongly complementary. The pericarp primarily provides rapid-response defense through analgesic and antibacterial mechanisms; the leaves contribute protective regulation through antioxidant and preservative effects; and the seeds support systemic metabolic homeostasis through lipid-mediated pathways. This complementary distribution forms a pharmacological continuum extending from immediate symptom relief to preventive protection and long-term physiological regulation. Such an integrated functional framework provides compelling scientific evidence for the comprehensive utilization of the entire plant.

From the perspective of medicine-food homology, *Z. bungeanum* exemplifies the traditional concept that dietary materials can simultaneously serve therapeutic functions. Its pericarp has long been valued as both a culinary spice and medicinal agent for warming, pain relief, and pathogen inhibition, while modern studies increasingly validate the health-promoting potential of leaf- and seed-derived products. The convergence of traditional empirical use and contemporary pharmacological evidence highlights the unique significance of *Z. bungeanum* as a model species for exploring the scientific basis of medicine-food homology.

Nevertheless, current industrial development remains heavily concentrated on pericarp utilization, resulting in substantial underexploitation of leaves, seeds, and other byproducts. Future progress will depend on advancing comparative metabolomics, clarifying molecular mechanisms, establishing standardized quality-control systems, and promoting integrated whole-plant industrial models. Through the coordinated development of pericarp-based medicinal spices, leaf-derived antioxidants, and seed-based functional oils, *Z. bungeanum* can be transformed from a traditionally pericarp-centered crop into a fully valorized, high-value biological resource.

In conclusion, the comprehensive exploitation of different parts of *Z. bungeanum* not only deepens our understanding of its chemical and pharmacological complexity but also provides an important pathway for realizing its full potential as a medicine-food homology plant. Such progress will contribute significantly to sustainable agricultural development, high-value resource utilization, and the modernization of traditional medicinal food systems.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Zhang, M., Wang, J., Zhu, L., Li, T., Jiang, W., Zhou, J., *et al.* (2017) *Zanthoxylum bungeanum* Maxim. (Rutaceae): A Systematic Review of Its Traditional Uses, Botany, Phytochemistry, Pharmacology, Pharmacokinetics, and Toxicology. *International Journal of Molecular Sciences*, **18**, Article 2172. https://doi.org/10.3390/ijms18102172

[2] Huang, Y., Gong, Z., Yan, C., Zheng, K., Zhang, L., Li, J., *et al.* (2023) Investigation on the Mechanisms of *Zanthoxylum bungeanum* for Treating Diabetes Mellitus Based on Network Pharmacology, Molecular Docking, and Experiment Verification. *BioMed Research International*, **2023**, Article ID: 9298728. https://doi.org/10.1155/2023/9298728

[3] Song, T. (2018) Studies on the Constituents of *Zanthoxylum bungeanum* Maxim and

Zanthoxylum armature DC. Master's Thesis, Lanzhou University of Technology.

[4] Chen, J. (2018) Studies on the Constituents from *Zanthoxylum bungeanum* Maxim. and Their Biological Activities. Ph.D. Thesis, Shenyang Pharmaceutical University.

[5] Wu, Y., Zhuo, Z., Qian, Q. and Xu, D. (2024) Chemotaxonomic Variation of Volatile Components in *Zanthoxylum bungeanum* Peel and Effects of Climate on Volatile Components. *BMC Plant Biology*, **24**, Article No. 793. https://doi.org/10.1186/s12870-024-05485-8

[6] Yang, X. (2008) Aroma Constituents and Alkylamides of Red and Green Huajiao (*Zanthoxylum bungeanum* and *Zanthoxylum schinifolium*). *Journal of Agricultural and Food Chemistry*, **56**, 1689-1696. https://doi.org/10.1021/jf0728101

[7] Wei, D., Zhao, Y., Zhang, M., Zhu, L., Wang, L., Yuan, X., *et al.* (2021) The Volatile Oil of *Zanthoxylum bungeanum* Pericarp Improved the Hypothalamic-Pituitary-Adrenal Axis and Gut Microbiota to Attenuate Chronic Unpredictable Stress-Induced Anxiety Behavior in Rats. *Drug Design*, *Development and Therapy*, **15**, 769-786. https://doi.org/10.2147/dddt.s281575

[8] Cao, Y., Ren, M., Yang, J., Guo, L., Lin, Y., Wu, H., *et al.* (2022) Comparative Metabolomics Analysis of Pericarp from Four Varieties of *Zanthoxylum bungeanum* Maxim. *Bioengineered*, **13**, 14815-14826. https://doi.org/10.1080/21655979.2022.2108632

[9] Liu, J. (2023) Study on the Chemical Composition and Biological Activity of Ethyl Acetate Part of Pericarps of *Zanthoxylum bungeanum* Maxim. Master's Thesis, Southwest Jiaotong University.

[10] Wu, T., Zhong, L., Hong, Z., Li, Y., Liu, X., Pan, L., *et al.* (2015) The Effects of *Zanthoxylum Bungeanum* Extract on Lipid Metabolism Induced by Sterols. *Journal of Pharmacological Sciences*, **127**, 251-259. https://doi.org/10.1016/j.jphs.2014.12.002

[11] Zhang, Y., Wang, M., Dong, H., Yu, X. and Zhang, J. (2017) Anti-Hypoglycemic and Hepatocyte-Protective Effects of Hyperoside from *Zanthoxylum bungeanum* Leaves in Mice with High-Carbohydrate/High-Fat Diet and Alloxan-Induced Diabetes. *International Journal of Molecular Medicine*, **41**, 77-86. https://doi.org/10.3892/ijmm.2017.3211

[12] Cheng, J., Tan, L., Lu, X., Zheng, M., Xu, C., Xu, W., *et al.* (2024) Photosynthetic Toxicological Effects of Organic Extracts from *Zanthoxylum bungeanum* Leaves on Controlling the *Microcystis aeruginosa* Blooms. *Current Microbiology*, **82**, Article No. 48. https://doi.org/10.1007/s00284-024-04026-8

[13] Jiao, X., Li, J., Sun, L., Wang, J., Wang, D., Shi, Z., Zhao, M. and Zhang, S. (2022) Study on the Chemical Components of the *Zanthoxylum bungeanum* Maxim. Leaves. Journal of Qiqihar University (*Natural Science Edition*), **38**, 60-63. (In Chinese)

[14] Lou, J. (2019) The Study on the Pharmacological Activities and Chemical Constituents from Barks of *Zanthoxylum bungeanum* Maxim. Master's Thesis, University of Jinan.

[15] Li, C. (2021) Study on the Chemical Constituents and Biological Activities of *Zanthoxylum bungeanum* Maxim. Master's Thesis, Northwest Minzu University.

[16] Han, S., Ren, P., Yang, B. and Cao, X. (2019) Review of Extraction, Chemical Composition and Application Status of Prickly Ash Seeds Oil. *Shandong Chemical Industry*, **48**, 88-89. (In Chinese)

[17] Wang, R., Guo, S., Duan, J., Zhu, Z., Su, S., Ouyang, Z. and Xue, J. (2016) Analysis and Evaluation of Resourceful Chemical Compositions in Different Parts of *Zanthoxylum bungeanum* Fruit and Its Seed Oil. *China Journal of Chinese Materia Medica*,

41, 2781-2789. (In Chinese)

[18] Mu, Y., Huang, Y. and Zhang, H. (2021) Bioactive Compounds Extracted with Different Solvents from *Zanthoxylum bungeanum* Maxim. Seeds and Comparison of Their Antioxidant Activities. *Packaging and Food Machinery*, **39**, 21-26. (In Chinese)

[19] Wang, Y., Yang, S.H., Zhong, K., Jiang, T., Zhang, M., Kwan, H.Y., *et al.* (2020) Network Pharmacology-Based Strategy for the Investigation of the Anti-Obesity Effects of an Ethanolic Extract of *Zanthoxylum bungeanum* Maxim. *Frontiers in Pharmacology*, **11**, Article ID: 572387. https://doi.org/10.3389/fphar.2020.572387

[20] Zhang, Z., Shen, P., Liu, J., Gu, C., Lu, X., Li, Y., *et al.* (2017) *In Vivo* Study of the Efficacy of the Essential Oil of *Zanthoxylum bungeanum* Pericarp in Dextran Sulfate Sodium-Induced Murine Experimental Colitis. *Journal of Agricultural and Food Chemistry*, **65**, 3311-3319. https://doi.org/10.1021/acs.jafc.7b01323

[21] Zhang, Q., Li, R., Wang, L., Zhang, T., Qian, D., Tang, D., *et al.* (2022) Hydroxy-α-Sanshool Isolated from *Zanthoxylum bungeanum* Maxim. Has Antidiabetic Effects on High-Fat-Fed and Streptozotocin-Treated Mice via Increasing Glycogen Synthesis by Regulation of PI3K/Akt/GSK-3β/GS Signaling. *Frontiers in Pharmacology*, **13**, Article ID: 1089558. https://doi.org/10.3389/fphar.2022.1089558

[22] Xi, S., Guo, Y., Ma, X., Zhan, Z. and Jin, L. (2021) Research Progress on Chemical Constituents and Pharmacological Effects of *Zanthoxylum bungeanum*. *West China Journal of Pharmaceutical Sciences*, **36**, 717-722. (In Chinese)

[23] Feng, M., Luo, F., Xie, S., Chen, Z., Tan, J., Li, K., Chen, G. and Wang, D. (2024) Potential Molecular Mechanism of Quercetin in the Treatment of Diarrhea-Predominant Irritable Bowel Syndrome Revealed by Network Pharmacology, Molecular Docking and Experimental Validation. *Journal of Hainan Medical University*, **30**, 203-214. (In Chinese)

[24] Luo, Z., Liu, X., Xu, C., Yan, Y., Fu, M., Peng, M., *et al.* (2026) Exploring the Mechanism of *Zanthoxylum bungeanum* Essential Oil in Alleviating Acute Pruritus in Rats Based on Network Pharmacology, Molecular Docking, and Experimental Pharmacology. *Journal of Ethnopharmacology*, **357**, Article 120889. https://doi.org/10.1016/j.jep.2025.120889

[25] Li, X., Chen, M., Huang, C., Huang, S., Liu, J., Zhang, L. and He, M. (2025) Research Progress on Resource Utilization of *Zanthoxylum bungeanum* and Its Waste Products. *South China Agriculture*, **19**, 149-154. (In Chinese)

[26] Shao, L., Chen, S., Chen, L. and Wang, J. (2024) Research Progress of Chemical Constituents and Pharmacological Effects of *Zanthoxylum bungeanum* Volatile Oil. *Shandong Journal of Traditional Chinese Medicine*, **43**, 197-205. (In Chinese)

[27] Zhang, L., Wang, Y., Yang, L., Xu, C., Qin, R., Peng, M. and Luo, Z. (2025) Composition, Antibacterial and Antioxidant Activities of Essential Oils from *Zanthoxylum schinifolium* by Supercritical CO_2 Extraction and Steam Distillation. *Central South Pharmacy*, **23**, 2187-2192.

[28] Hu, M.-B., Gao, K.-X., Wang, Y. and Liu, Y.-J. (2023) Characterization of Polysaccharides from the Pericarp of *Zanthoxylum bungeanum* Maxim by Saccharide Mapping and Their Neuroprotective Effects. *Molecules*, **28**, Article 1813. https://doi.org/10.3390/molecules28041813

[29] Ma, L., Wang, C., Zhai, X., Wang, K., Sang, C., Wang, W., *et al.* (2022) Chemical Constituents from the Roots of *Zanthoxylum bungeanum* Maxim. and Their Neuroprotective Activities. *Fitoterapia*, **163**, Article 105337. https://doi.org/10.1016/j.fitote.2022.105337