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Progress in research on flavor compounds in *Gastrodia elata*

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Abstract

As a medicinal and edible plant, *Gastrodia elata* (*G. elata*) flavor compounds critically influence its sensory, nutritional, and medicinal properties. This review summarizes recent advances in *G. elata* flavor research. Volatile components, mainly comprising organic acids, aldehydes, alcohols, and esters, form its unique flavor profile, with 3-methylthiopropionaldehyde and 2,3,5,6-tetramethylpyrazine identified as key contributors to the characteristic "horse-urine odor." Variations in volatile composition exist among cultivars, geographical origins, and harvest seasons. Non-volatile compounds, including phenolics (e.g., gastrodin, parishins), saccharides, and free amino acids, underpin pharmacological efficacy and nutritional value. Conventional extraction techniques (steam distillation, solvent extraction) face limitations in efficiency and eco-friendliness, while processing methods (steaming, fermentation) significantly alter flavor profiles. Future research should focus on advanced identification technologies, sustainable extraction methods, mechanistic elucidation, and industrial applications to optimize *G. elata*'s utilization in food and pharmaceuticals.

Keywords: *Gastrodia elata*; Flavor compounds; Volatile components; Extraction techniques; Processing methods.

1. Introduction

Gastrodia elata (*G. elata*) is a perennial, saprophytic herb of the Orchidaceae family, primarily distributed across Asian countries such as China, Japan, South Korea, India, and Nepal. In China, it is predominantly cultivated in the Yunnan, Guizhou, and Hubei provinces, thriving in cool, humid forest environments rich in humus. These ecological conditions promote optimal growth and accumulation of characteristic flavor compounds. As a dual-purpose medicinal and edible plant, *G. elata* exhibits sedative, anti-inflammatory, and antioxidant properties (Kwon et al., 2013). In provinces like Yunnan and Guizhou of China, it is traditionally consumed as a tonic food. Its flavor compounds,serve as critical links between sensory perception and functional value, guidig consumer preferences while also acting as key carriers of its nutritional and medicinal functions (Chinese Pharmacopoeia Commission, 2020). Both the edible and medicinal qualities of *G. elata* are intrinsically linked to its flavor components (Wan et al., 2025), and processing techniques significantly influence the preservation of these flavor substances and bioactive constituents (Zuo,et al.,2018).

Recent advancements in analytical technologies have significantly accelerated research into the flavor chemistry of *G. elata*. Studies reveal that its distinctive flavor results from the synergistic interaction of volatile and non-volatile components. Volatile compounds are dominated by organic acids (accounting for up to 84.78%), aldehydes, and alcohols, with 3-methylthiopropionaldehyde and 2,3,5,6-tetramethylpyrazine (Figure 1) identified as key contributors to its characteristic "horse-urine odor" (Table 1). Non-volatile constituents, including gastrodin, parishins, polysaccharides, and free amino acids, play pivotal roles in pharmacological efficacy, textural properties, and nutritional functions. However, challenges persist in flavor research. On one hand, the chemical diversity of *G. elata* is strongly influenced by cultivar, geographical origin, harvest season, and processing methods. For instance, the volatile components differ

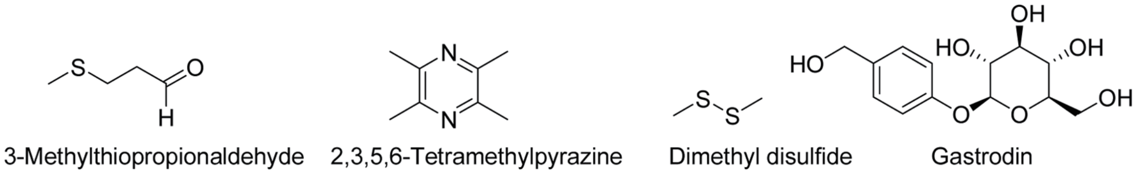


Figure 1. Structure of main compound associated with the horse-urine odor in *Gastrodia elata.*

Table 1. Volatile Chemical Components of *G. elata*

No.	Category	Example Compounds	Chemical Formula	Odor/Flavor Description	References
1	Aldehydes	Nonanal	$C_9H_{18}O$	Greasy fragrance	(Sun et al., 2022; Lu, 2016)
2		Hexanal	$C_6H_{12}O$	Floral, fruity fragrance	(Sun et al., 2022)
3		Heptanal	$C_7H_{14}O$	-	(Sun et al., 2022)
4		Hexadecanal	$C_{16}H_{32}O$	Cardboard-like odor	(Huang et al., 2018)
5		Benzaldehyde	C_7H_6O	-	(Sun et al., 2022)
6		Phenylacetaldehyde	C_8H_8O	Hyacinth-like aroma	(Tan et al., 2025; Sun et al., 2022)
7		2-Methylbutanal	$C_5H_{10}O$	Cocoa, almond-like odor	(Sun et al., 2022)
8		3-Methylbutanal	$C_5H_{10}O$	Chocolate, peach, and apple fragrances	(Li et al., 2025; Lu, 2016)
9		3-Methylthiopropionaldehyde	C_4H_8OS	Pungent, irritating odor	(Li et al., 2025)
10	Alcohols	Campesterol	$C_{28}H_{48}O$	-	(Xiong et al., 2014)
11		γ-Sitosterol	$C_{29}H_{50}O$	-	(Xiong et al., 2014)
12		Hexanol	$C_6H_{14}O$	-	(Sun et al., 2022)
13	Alcohols	Butanol	$C_4H_{10}O$	-	(Sun et al., 2022)
14		1-Octen-3-ol	$C_8H_{16}O$	-	(Guan et al., 2008)
15		Terpinen-4-ol	$C_{10}H_{18}O$	-	(Xiong et al., 2014; Guan et al., 2008)
16		Phenethyl alcohol	$C_8H_{10}O$	Honey-like aroma	(Tan et al., 2025)
17		Isoamyl alcohol	$C_5H_{12}O$	Nail polish and greasy odor	(Tan et al., 2025)
18	Esters	Methyl palmitate	$C_{17}H_{34}O$	Waxy, fatty, iris-like odor	(Guan et al., 2008)
19		Ethyl palmitate	$C_{18}H_{36}O_2$	-	(Guan et al., 2008)
20		Ethyl linoleate	$C_{19}H_{34}O_2$	-	(Guan et al., 2008)
21	Acids	Acetic acid	$C_2H_4O_2$	-	(Han et al., 2018)
22		Hexanoic acid	$C_6H_{12}O_2$	Sweaty odor	(Han et al., 2018)
23		Nonanoic acid	$C_9H_{18}O_2$	-	(Han et al., 2018)
24		n-Hexadecanoic acid	$C_{16}H_{32}O_2$	-	(Xiong et al., 2014)
25		1-Methoxyethyl hexadecanoate	$C_{19}H_{38}O$	-	(Guan et al., 2008)
26		Linolenic acid	$C_{18}H_{30}O_2$	-	(Han et al., 2018)
27		Linoleic acid	$C_{18}H_{32}O_2$	-	(Xiong et al., 2014)
28	Acids	Palmitic acid	$C_{16}H_{32}O_2$	-	(Guan et al., 2008)
29		Linoleic acid	$C_{18}H_{32}O_2$	Mild fatty odor	(Huang et al., 2018)
30	Phenols	2,4-Di-tert-butylphenol	$C_{14}H_{22}O$	Phenolic odor	(Huang et al., 2018)

(continued)

Table 1. *(continued)*

No.	Category	Example Compounds	Chemical Formula	Odor/Flavor Description	References
31		4-Methylphenol	C_7H_8O	Narcissus, acacia, and mimosa-like fragrances	(Sun et al., 2022; (Guan et al., 2008)
32		p-Cresol	C_7H_8O	Strong phenolic and tobacco-like aroma (urine-like odor)	(Tan et al., 2025;Han et al., 2018)
33		Eugenol	$C_{10}H_{12}O_2$	Sweet, spicy, clove-like aroma with strong carnation and musk notes	(Huang et al., 2018)
34	Ketones	Acetone	C_3H_6O	-	(Sun et al., 2022)
35		2-Butanone	C_4H_8O	-	(Sun et al., 2022)
36		3-Nonanone	$C_9H_{18}O$	-	(Sun et al., 2022)
37		Acetophenone	C_8H_8O	Cheesy, sweet, almond-like	(Tan et al., 2025; Han et al., 2018)
38	Alkanes	Isopentane	C_5H_{12}	Pleasant aromatic odor	(Lu, 2016)
39	Alkanes	Tetradecane	$C_{14}H_{30}$	Mild waxy odor	(Huang et al., 2018)
40		Pentadecane	$C_{15}H_{32}$	-	(Han et al., 2018)
41		Hexadecane	$C_{16}H_{34}$	Mild waxy odor	(Han et al., 2018)
42		Eicosane	$C_{20}H_{42}$	-	(Han et al., 2018)
43		Triacontane	$C_{30}H_{62}$	-	(Han et al., 2018)
44		Farnesane	$C_{15}H_{26}$	-	(Han et al., 2018)
45	Aromatics	Naphthalene	$C_{10}H_8$	Spicy, tar-like odor	(Huang et al., 2018)
46		Phenanthrene	$C_{14}H_{10}$	Spicy, tar-like odor	(Huang et al., 2018)
47	Others	Styrene	C_8H_8O	-	(Guan et al., 2008)
48		trans-Squalene	$C_{30}H_{50}$	-	(Han et al., 2018)
49		Limonene	$C_{10}H_{16}$	Lemon-like aroma	(Guan et al., 2008)
50		α-Pinene	$C_{10}H_{16}$	Pine, coniferous, and resinous odor	(Guan et al., 2008)
51		2-Pentylfuran	$C_9H_{14}O$	Fruity, earthy, green, and vegetable-like aroma	(Guan et al., 2008; Yang et al., 2024)
52	Others	2,3,5,6-Tetramethylpyrazine	$C_8H_{12}N$	Musty odor	(Guan et al., 2008)
53		Dimethyl disulfide	$C_2H_6S_2$	Sulfurous, foul odor	(Lu, 2016)

significantly between red and green ecotypes, and the contents of gastrodin and palisin were dynamically changed by steaming and boiling processes (Xiong et al., 2014; Qiu et al., 2019). On the other hand, existing extraction techniques (e.g., steam distillation, supercritical CO_2 extraction), despite their advantages, face limitations in trace compound identification, thermosensitive component protection, and eco-efficient extraction. Furthermore, the mechanisms linking flavor compounds to bioactivities, as well as the molecular basis of flavor evolution during processing, remain inadequately elucidated, hindering product innovation and industrial upgrading.

This paper systematically reviews research progress on *G. elata* flavor compounds, focusing on the classification, functions, and influencing factors of both volatile and non-volatile components. It also compares extraction technologies and processing methods, and proposes future research directions to advance theoretical foundations for deep resource utilization, flavor regulation, and value-added applications of *G. elata*.

2. Types and characteristics of flavor compounds

The volatile components of *G. elata* constitute the foundational elementsof its distinctive flavor profile. Common chemical constituents include phenolic glycosides, saccharides and their glycosides, steroids, organic acids and their esters, nucleosides, amino acids and derivatives, among others. The unique flavor and bioactive functions of *G. elata* primarily originate from tuber-stored compounds, which are key secondary metabolites responsible for generating numerous potentially bioactive substances. Researchers have conducted comprehensive studies on its chemical composition, having isolated and identifyed over 200 compounds from *G. elata* tubers. These compounds are primarily categorized into phenolic compounds, parishins, phenol-amino acid conjugates, phenol-nucleotide derivatives, and carbohydrate derivatives (Zhu et al., 2021).

The sensory perception of food typically initiates with olfactory stimulation triggered by volatile substances that carry characteristic aromas. In G. elata, itsdistinctive fragrance has been specifically attributed to volatile organic compounds (Sun et al., 2020). While non-volatile compounds primarily mediate its taste-active properties, they also demonstrate significant biological functions and pharmacological efficacy.

2.1. Volatile flavor compounds

Supercritical CO_2 extraction was utilized for the selective isolation of volatile components from *G. elata*, with subsequent compositional analysis conducted via gas chromatography-mass spectrometry (GC-MS). The volatile compounds idebtified in the study mainly consist of aldehydes, phytols, esters, alkanes, alkenes, phenols, organic acids, and nitrogen-containing compounds (Table 1). Among these, organic acids demonstrated the most prominent abundance and structural diversity, accounting for 84.78% of the total identified components. The synergistic interplay of these components likely underlies the distinctive sensory characteristics associated with *G. elata* rhizomes(Han et al., 2018).

A comprehensive review of recent literature on *G. elata* volatile oils reveals its rich chemical composition, as summarized in Table 1. Key components include aldehydes, alcohols, esters, acids, phenols, ketones, alkanes, aromatic compounds, and other volatile substances. These collectively define its unique sensory attributes. Through GC-MS analysis, critical constituents such as γ-sitosterol, linoleic acid, n-hexadecanoic acid, and stigmasta-3,5-diene have been identified (Xiong et al., 2014). However, discrepancies in reported volatile compositions and relative abundances persist across studies, primarily attributed to variations in analytical techniques, equipment specifications, *G. elata* cultivars, and geographical origins. Notably,a significant proportion of compounds remain uncharacterized, highlighting the need for methodological refinements and advanced analytical technologies to achieve comprehensive analysis and comprehensive characterization of *G. elata* volatile oils.

Aldehydes, typically formed through fatty acid oxidation, impart unique aromas at low concentrations but exhibit rancid or pungent odors when exceeding critical thresholds (Wang et al., 2021). Their relative content ranges from 35.60% to 57.06%, collectively representing a significant proportion of *G. elata* volatile oils (Sun et al., 2022; Lu, 2016). Specific aldehydes contribute distinct sensory attributes: nonanal delivers fatty-grassy notes with citrus undertones; phenylethanal and hexanal enhance floral and fruity nuances; hexadecanal introduces cardboard-like olfactory characteristics; 2-methylbutanal evokes cocoa and almond aromas; and 3-methylbutanal imparts chocolate and peach-like fragrances (Li et al., 2025). Notably, 3-methylthiopropionaldehyde generates a sharp, pungent odor, strongly associated with the characteristic "horse-urine odor" of *G. elata* (Martinez-Arellano et al., 2016).

Alcohols, derived from microbial metabolism of protein-derived amino acids and lipid peroxidation (Domínguez et al., 2014), predominantly contribute pleasant floral-fruity notes to the flavor profile (Xia et al., 2021; Huang et al.,2018) identified alcohols as the second-largest volatile group (relative content: 39.07%) using simultaneous distillation extraction coupled with GC-MS (SDE-GC-MS). Esters, accounting for 20.00–23.92% of volatile oils, include methyl palmitate with waxy-greasy tones, which significantly shape the organoleptic profile(Sun et al., 2022; Huang et al., 2018).

Organic acids, comparable to aldehydes in diversity, are characterized by linoleic acid (mild fatty note) and α-linolenic acid (dominant at 52.29%) as key components (Han et al., 2018). Hexanal, hexanoic acid, and phenethyl alcohol synergistically exert synergistic modulation the aroma: hexanoic acid, with sweaty undertones, may partially explain *G. elata*'s distinct odor (Tan et al., 2025). 4-Methylphenol, contributing narcissus-acacia-mimosa aromatic profiles, comprises up to 20.41% in *G. elata* volatiles (Guan et al., 2008; Huang et al., 2018). The aromatic characteristics of eugenol is more complex, with clove flavor, wood flavor and rich caryophylla musk smell, which belongs to the edible spices classified as an approved food additive in China.

Ketones demonstrate chain-length-dependent aromas: short-chain variants emit fatty-toasty notes, while long-chain counterparts produce floral aromatic tones. Phenethyl alcohol and acetophenone further enrich the sensory profile with buttery-floral-fruity nuances accompanied by honeyed-cheesy accents(Tan et al., 2025). Alkanes (7.97–16.63%) comprise tetradecane/hexadecane (mild waxiness) and isopentane (mildly pleasant olfactory characteristics) (Huang et al., 2018; Lu, 2016). Aromatic compounds like naphthalene contribute spice-like and tar-like characteristics.

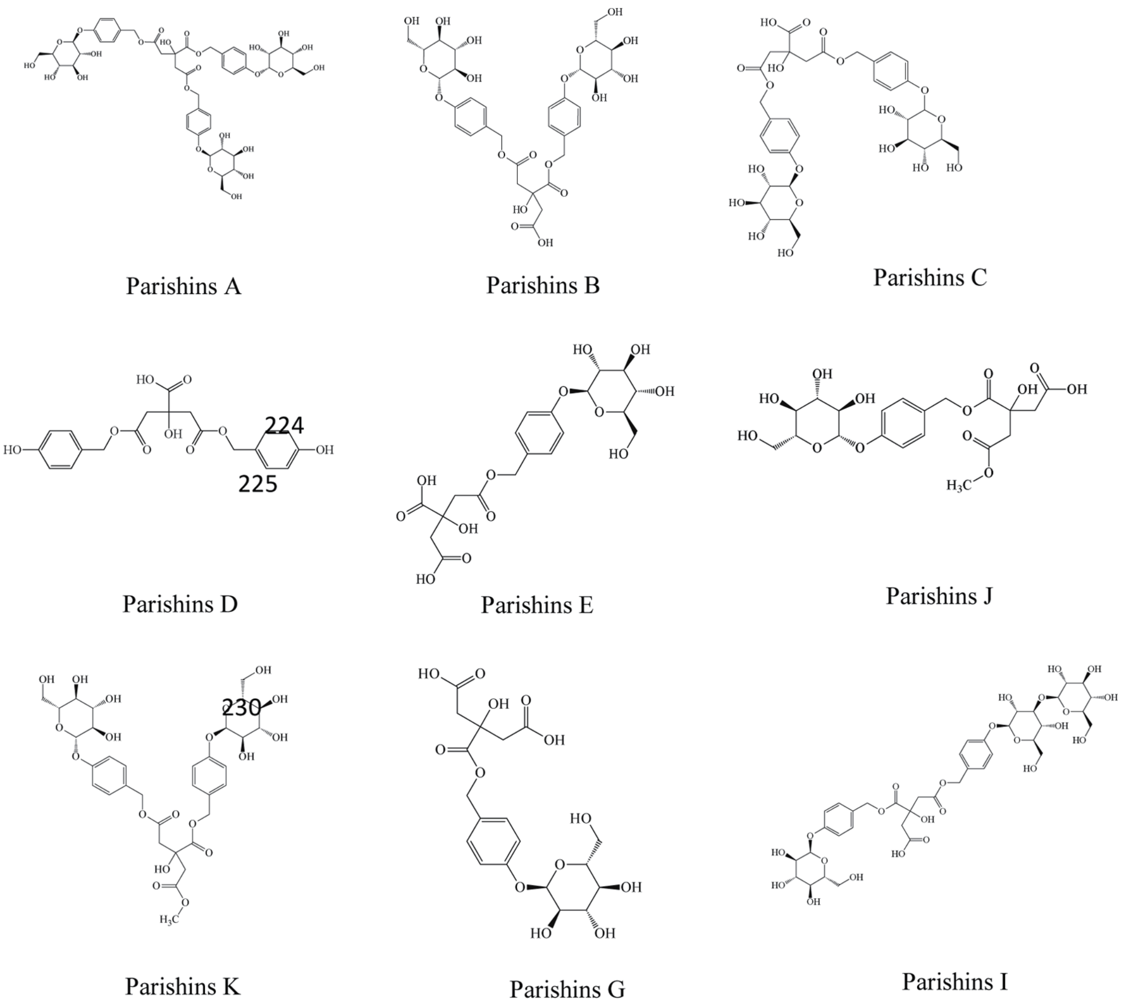
Notably, 2,3,5,6-tetramethylpyrazine (musty odor) and dimethyl disulfide (sulfuric rancidity), combined with hexanoic acid's sweat-like note, are implicated in *G. elata*'s off-flavors (Tan et al., 2025; Lu, 2016; Zhao et al., 2021; Cao et al., 2018). The chemical structure of dimethyl disulfide is depicted in Figure 1. Studies demonstrate that alkanes, aromatic compounds, and sulfur -containing compounds collectively account for 81.42% of the distinctive aroma in black ecotype (Guizhou Bijie population) through integrated electronic nose and GC-MS analyses.

Critical bioactive constituents such as hexadecanoic acid, α-linolenic acid, and trans-squalene may underlie *G. elata*'s therapeutic efficacy in against neoplastic, neuropsychiatric, and metabolic disorders. The synergistic interactions of these compounds underpin both its organoleptic properties and therapeutic value (Jin et al., 2021).

Significant variations in flavor profiles are observed among different cultivars and provenances of *G. elata*. The volatile organic components of the green ecotype are predominantly ethyl linoleate and styrene, whereas the red ecotype is characterized by 2-pentylfuran and E,E-2,4-decadienal. These two ecotypes exhibit significant quantitative differences in both the chemical diversity and concentration gradients of volatile compounds (Xiong et al., 2014; Guan et al., 2008). Pharmacognostic studies have revealed distinct variations in volatile content and composition among raw medicinal materials harvested seasonally. Similarly, *Cinnamomum* spp. of varying ages demonstrate phytochemical divergence in the constituent profiles of volatile oil constituents (Ni et al., 2004; Huang et al., 2005), suggesting that disparities in volatile composition may originate from microenvironmental conditions, microclimate variations, physiological states, and morphological differences during plant growth.

2.2. Non-volatile flavor compounds

As a traditional medicinal herb, the chemical composition of *G. elata* was first investigated in the 1930s (Mar, 1936). Non-volatile chemical constituents constitute the pharmacologically active basis, exerting therapeutic effects including endogenous wind suppression (anticonvulsant activity), liver yang hyperactivation inhibition, meridian obstruction relief, and sedative-hypnotic regulation (Chinese Pharmacopoeia Commission, 2020). Additionally, *G. elata* demonstrate significant neuroprotective efficacy in cognitive enhancement, antiepileptic activity, cardiovascular homeostasis modulation, and symptomatic alleviation of cephalalgia and peripheral neuropathy (He et al., 2023; Sun et al., 2023). Its primary non-volatile flavor-active compounds primarily include



Parishins A
Parishins B
Parishins C
Parishins D
Parishins E
Parishins J
Parishins K
Parishins G
Parishins I

Figure 2. Structures of the nine most studied parishin-type compounds.

phenolic glycosides, heteropolysaccharides, phytosterols, and organic acids.

2.2.1. Phenolic compounds

Gastrodin (4-(hydroxymethyl)phenyl-β-D-glucopyranoside), a phenolic glycoside, serves as both a primary bioactive constituent and a key flavor determinant in *G. elata* . Its chemical structures is illustrated in Figure 1. As the chemical marker for quality standardization, gastrodin constitutes the principal criterion in *G. elata* product authentication(Li et al., 2019). Phytochemical investigations further reveal *G. elata* also contains phenolic compounds such as p-hydroxybenzyl alcohol and Parishins, which concurrently mediate therapeutic efficacy and organoleptic characteristics(Sun et al., 2022).

p-Hydroxybenzyl alcohol, the aglycone of gastrodin, along with gastrodin itself, constitutes the primary pharmacological basis for *G. elata*'s therapeutic efficacy in synergy with gastrodin. These compounds demonstrate significant bioactivities, including sedation, anticonvulsant action, analgesia, neuroprotective, cardioprotective, antihypertensive effects, and anti-thrombotic/antiplatelet aggregation properties (Guo et al., 2014; Li et al., 2015).

Parishins (synonym: Balishanglycosides) are phenolic ester glucosides isolated from *G. elata*. Structurally, they structurally characterized by citric acid derivatives esterified with 4-hydroxybenzyl alcohol or its derivatives via ester bonds. Parishins act as biotransformation precursors of gastrodin and are typically present in higher concentrations than gastrodin itself in raw *G. elata* (Zhang et al., 2022). However, Parishins are thermally unstable and prone to degradation. During processing methods involving heat (e.g., steaming or boiling), the ester bonds in Parishins were hydrolyzed, leading to a marked increase in gastrodin content post-processing (Yuan et al., 2008). The 2020 edition of the Chinese Pharmacopoeia established a quality control markers for *G. elata* using gastrodin, p-hydroxybenzyl alcohol, and Parishins A, B, C, and E as marker peaks (Chinese Pharmacopoeia Commission, 2020). To date, 33 Parishin analogs have been structurally elucidated in *Gastrodia elata*, with nine Parishins A, B, C, D, E, J, K, G, and I documented. Their chemical structures are illustrated in Figure 2 (Zhang et al., 2020).

G. elata is chemically characterized by diverse polyphenolic constituents beyond gastrodin, p-hydroxybenzyl alcohol, and parishins, including phenolic derivatives (p-hydroxybenzaldehyde, vanillyl alcohol, vanillin, syringic acid), flavanols (catechin, epicatechin), phenylpropanoids (caffeic acid, cinnamic acid), and specialized metabolites (gastrodophenols A/B, quercetin)(Zhan et al., 2016; Chen et al., 2023).

2.2.2. Carbohydrates

Carbohydrates in *G. elata* comprise of small-molecule sugars (monosaccharides, disaccharides, and glycosides) and polysaccharides (Ji et al., 2025). *G. elata* polysaccharides (GEPs) are key bioactive components with immune-regulatory and anti-neoplastic effects, while also influencing the herb's texture and mouthfeel. Structurally, GEPs are predominantly contain glucose monomers, absence of uronic acid residues, proteoglycans, or ketoses, and are classified as neutral homopolysaccharides polysaccharides (Shang et al., 2024). Researchers isolated water-extracted (WGEW) and alkali-extracted (AGEW) polysaccharides, while Li et al. characterized two distinct polysaccharides, GBP-I and GBP-II (Qiu et al., 2007; Li et al., 2008). Studies have demonstrated that GEPs exhibit therapeutic multifunctionality, including immune regulation, senescence retardation effects, and antihypertensive properties (Wang et al., 2022; Wu et al., 2022). Structurally modified GEPs demonstrate superior targeted efficacy in reactive oxygen species scavenging and malignant cell proliferation inhibition(Dou, 2022). These biochemical attributes underscore the potential of *G. elata* in pharmaceutical and nutraceutical industries. Glycosides, with their structural stability and higher bioavailability compared to polysaccharides, also hold significant promise for development(Ji et al., 2025).

2.2.3. Organic acids

G. elata is chemically characterized by small-molecule organic acids such as oxalic acid, malic acid, citric acid, and succinic acid, which mediate pH regulation and contribute to its organoleptic characteristics. These acids serve pivotal roles in defining the herb's organoleptic properties(Yang et al., 2024; Yang et al., 2019). Pharmacological investigations demonstrate that non-volatile organic acids in traditional Chinese medicine exhibit antioxidant, hepatoprotective, immunomodulatory, antimicrobial, and antiviral bioactivities(Tang et al., 2012). Notably, citric acid is essential to the biosynthesis of Parishins, indicating metabolic coordination with phenolic glycosides in *G. elata*. Consequently, the diversity and concentration of organic acids are critical evaluation metrics for evaluating the herb's quality, medicinal efficacy, and phytochemical applications.

2.2.4. Free amino acids

Free amino acids, the fundamental proteinogenic precursors and essential components of human physiology, serve pivotal roles in regulating nitrogen balance, immune potentiation, and promoting metabolic vitality (Neinast et al., 2019; Solon-Biet et al., 2019). As a dual-purpose medicinal and edible resource, the free amino acids in *G. elata* reflect its nutritional value (Yan et al., 2023). The herb contains a comprehensive profile of amino acids with high nutritionally complete (Zhu et al., 2024), categorized as follows: sweet-tasting amino acids: Threonine (Thr), Serine (Ser), Glycine (Gly), and Alanine (Ala) (4 types); bitter-tasting amino acids: Valine (Val), Methionine (Met), Isoleucine (Ile), Leucine (Leu), Tyrosine (Tyr), Phenylalanine (Phe), Histidine (His), and Arginine (Arg) (8 types); umami-tasting amino acids: Aspartic acid (Asp) and Glutamic acid (Glu) (2 types); and non-flavor-active amino acids: Cysteine (Cys), Lysine (Lys), and Proline (Pro) (3 types).

Processing methods significantly influence amino acid content. Immersion in water leads to partial leaching, while heat treatment induces decomposition (Kong et al., 2017). Techniques such as steaming, boiling, and lactic acid fermentation reduce bitter amino acids by 72.56–87.51%, effectively mitigating bitterness and improving palatability (Yang et al., 2024). Furthermore, post-harvest processing methods (e.g., drying protocols) and morphological variations of *G. elata* markedly alter amino acid composition and concentration. Consequently, processing strategies are pivotal for flavor modulation and sensory optimization in both culinary and medicinal applications.

3. Extraction techniques for flavor compounds in *G. elata*

The isolation and identification of chemical constituents in *G. elata* require specialized extraction and analytical methods. Thus, extracting flavor compounds is the methodological foundation in studying its flavor profile. Common extraction techniques are summarized in Table 2.

Steam distillation is a classical method for extracting volatile components, it is simple operational requirements with minimal equipment requirements. However, risks thermal degradation thermolabile compounds through isomerization or decomposition, compromising flavor integrity. Guan et al. applied this method to extract volatiles from the secondary tubers of *G. elata* and identified them via GC-MS (Guan et al., 2008). Solvent extraction uses organic solvents for compound isolation. While straightforward, it risks solvent residue contamination. Supercritical CO_2 extraction is noted for preserving volatile compound integrity, this method was employed by Han Yu et al. to extract *G. elata* volatiles. Thirty compounds were identified via GC-MS (Han et al., 2018). Headspace-Gas Chromatography-Mass Spectrometry (HS-GC-MS) is a rapid, precise method requiring minimal sample volume, and this method was directly used to analyze volatile components in powdered *G. elata*. Qiu et al. detected 61 volatiles, with 25 characterized (Qiu et al., 2019). Solid-Phase Microextraction (SPME) enriches volatiles using fiber-coated adsorbents, followed by GC-MS analysis. Qiu et al. utilized HS-SPME-GC-MS to analyze *G. elata* powder, identifying 61 volatiles (25 characterized). This method is demonstrating particular efficacy for rapid volatile profiling in dried samples (Qiu et al., 2019). Microwave-Assisted Extraction (MAE) accelerates compound dissolution via microwave irradiation, offering high-efficiency and reduced solvent use. Zuo et al. optimized MAE for extracting gastrodin and p-hydroxybenzyl alcohol, validated by HPLC. Results showed HPLC-optimized protocol with minimal processing time (Zuo et al., 2018). Simultaneous Distillation-Extraction (SDE) concurrently heats aqueous and organic phases, enabling volatile concentration with minimal solvent. Coupled with GC-MS (SDE-GC-MS), it supports qualitative and quantitative analysis but carries solvent residue risks (Huang et al., 2018).

The extraction and identification of *G. elata* flavor compounds involve diverse techniques, each with unique advantages and limitations. Selecting the optimal method based on research objectives ensures efficient and accurate outcomes.

4. Processing techniques of *G. elata*

The processing of *G. elata* is a critical determinant of its flavor and bioactive components. Commonly used methods such as steaming, boiling, and fermentation alter its physicochemical properties and significantly influence the composition and concentration of flavor compounds.

Table 2. Flavor Extraction Techniques for G. elata

Category	Technique	Description	References
Traditional Techniques	Steam Distillation	Uses steam to carry volatile components from *Gastrodia elata*, followed by condensation and separation.	(Guan et al., 2008)
	Solvent Extraction	Employs organic solvents (e.g., ethanol, methanol) to extract flavor compounds.	(Li et al., 2019)
Modern Techniques	Supercritical CO_2 Extraction	Utilizes supercritical CO_2 as a solvent for high-efficiency and residue-free extraction, preserving volatile components.	(Han et al., 2018)
	Headspace-GC/MS	Directly analyzes volatile components in processed *Gastrodia elata* using headspace sampling coupled with gas chromatography-mass spectrometry.	(Qiu et al., 2019)
	Solid-Phase Microextraction (SPME)	Adsorbs volatile components onto coated fibers, followed by GC-MS analysis for enrichment and identification.	(Qiu et al., 2019)
	Microwave-Assisted Extraction	Enhances extraction efficiency through microwave irradiation.	(Ma et al., 2010)
	Simultaneous Distillation-Extraction	Combines steam distillation and solvent extraction to simultaneously extract components.	(Huang et al., 2018)

4.1. *Steaming process*

Steaming, a traditional method, involves treating *G. elata* with high-temperature steam to induce physical and chemical changes. This process achieves enzyme inactivation and glycoside preservation (Zuo et al., 2018), effectively halting enzymatic degradation of key compounds. Upon post-steaming, gastrodin content increases, while p-hydroxybenzyl alcohol levels decrease (Yang et al., 2019). Fresh *G. elata* is rich in adenosine, but steaming reduces its content by approximately 50%. Subsequent drying methods (e.g., hot-air or freeze-drying) partially restore adenosine levels, with hot-air drying increasing adenosine by 2.6–2.7-fold increases compared to steamed samples (Wu et al., 2022). Additionally, steaming softens the herb's texture, facilitating further processing and consumption.

4.2. *Boiling process*

Boiling involves immersing *G. elata* in boiling water to solubilize internal components. This method extracts water-soluble compounds such as polysaccharides and amino acids into the aqueous phase. Compared to steaming, boiling significantly reduces polysaccharide content but increases water-soluble protein levels (Yang et al., 2024). It also lowers organic acids and bitter-taste amino acids, thereby improving sensory acceptability.

4.3. *Fermentation process*

Fermentation, an emerging technique, leverages microbial activity to transform *G. elata*'s chemical profile. After fermentation, polysaccharide and water-soluble protein contents rise, while organic acid and free amino acid compositions shift dynamically (Yang et al., 2024). Notably, fermentation mitigates undesirable odors (e.g., "horse-urine-like off-flavor")and enhances sensory acceptance (Tan et al., 2025).

5. Concluding remarks

Although significant progress has been made in the study of flavor compounds in *G. elata*, several challenges remain unresolved. Future research should focus on leveraging advanced analytical technologies to conduct an in-depth exploration of flavor profiles, particularly the identification of trace flavor components and comprehensively elucidating their composition.

The development of high-efficiency, eco-friendly, and cost-effective extraction techniques is essential to improve the yield and purity of flavor compounds while minimizing environmental impact. Synergistic applications of multiple extraction methods should also be explored to harness their complementary advantages.

Further investigation into the mechanistic roles of *G. elata* flavor compounds in food and pharmaceutical systems is critical to establish a robust molecular basis for their rational utilization. Building on these insights, translational product innovation in functional foods, nutraceuticals, and pharmaceuticals should be prioritized to meet consumer demands, expand market applications, and promote the sustainable growth of the *Gastrodia elata* industry.

In summary, *G. elata* possesses a rich diversity of flavor compounds, encompassing both volatile and non-volatile constituents, which collectively define its unique sensory attributes. While various extraction technologies and processing strategies have been established, ongoing research holds promise for unlocking the full potential of these compounds, paving the way for new opportunities in the industrial transformation of *G. elata*.

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