A Comparative Study of the Chemical Compositions of Heartwood and Sapwood in *Erythrophleum fordii*

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The chemical composition, lignin structure, and extractive profiles of sapwood and heartwood were studied for 18-year-old *Erythrophleum fordii* trees to elucidate their chemical disparities and potential for high-value utilization. The cellulose, hemicellulose, and lignin contents were higher in sapwood than in heartwood. In contrast, heartwood exhibited significantly higher ash content, moisture content, and yields of various extractives, along with greater acidity. FTIR spectroscopy revealed SG-type lignin in both sapwood and heartwood, dominated by syringyl units. Heartwood formation did not alter the fundamental lignin structure but increased its condensation degree and reduced the characteristic hemicellulose absorbance. Notably, the heartwood was the primary site for bioactive constituent enrichment, with total phenolic and flavonoid contents (19.9 mg GAE/g DW and 36.5 mg RE/g DW, respectively) 4.3 and 5.6 times higher than those in sapwood. GC-MS analysis further showed that heartwood extractives were rich in terpenoids and sterols (*e.g.*, vitamin E, stigmasterol, and β-sitosterol), compounds known for their antioxidant, cholesterol-lowering, and pharmaceutical properties. These findings underscore the potential of *E. fordii* heartwood for developing functional natural products and as a source of pharmaceutical raw materials.

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INTRODUCTION

Wood is primarily composed of cellulose, hemicellulose, lignin, and extractives. Cellulose, the most abundant and widely distributed renewable resource in nature, accounts for over 50% of the carbon in the plant kingdom. It is a linear high-molecular-weight polymer consisting of β-D-glucopyranose units linked by β-1,4-glycosidic bonds, with the formula $(C_6H_{10}O_5)_n$, and it contains both crystalline and amorphous regions (Altgen *et al.* 2023). In contrast, hemicellulose is an amorphous polymer with a branched structure and low degree of polymerization. Its composition varies significantly between hardwoods and softwoods; hardwoods typically contain glucuronoxylan as the main hemicellulose, while softwoods are rich in glucomannan, indicating a non-uniform composition across wood types (Abik *et al.* 2023). Lignin, the second most abundant amorphous polymer in nature after cellulose, forms a three-dimensional network of phenylpropane units interconnected by ether and C–C bonds (Xu *et al.* 2020). Although present in minor amounts, wood extractives are highly diverse and include terpenoids, phenolics, aliphatic compounds, quinones, naphthoquinones, simple sugars, sugar alcohols, suberin, and other aliphatic esters. They are distributed within anatomical structures such as vessels and axial parenchyma cells (Ma *et al.* 2025).

The chemical composition of wood is a fundamental factor determining its overall properties. The content and arrangement of cellulose within the cell wall directly influence the mechanical strength of wood (Ruiz-Aquino *et al.* 2019). Hemicellulose, rich in hydrophilic groups such as hydroxyl and carbonyl, critically affects wood hygroscopicity, shrinkage, and dimensional stability. Lignin contributes to wood color formation through chromophores such as coniferaldehyde and carbonyl groups, as well as its specific ultraviolet absorption characteristics; however, wood color is also influenced by anatomy, the presence of cellulose, age, and weathering. Extractives, including compounds such as terpenoids, polyphenols, and pigments, possess intrinsic color and may undergo chemical transformations upon exposure to external factors like light and heat, leading to discoloration. Consequently, variations in extractive composition and content are key factors underlying the diversity of wood color among species. Furthermore, extractives affect other wood properties, such as permeability, decay resistance, and dimensional stability. The chemical composition of wood is not static but exhibits considerable variability across species, within the same species, and even within individual trees. This variability arises from factors such as genetic differences, growth conditions, tree age, and anatomical location (sapwood versus heartwood). Heartwood formation involves physiological and biochemical changes that lead to chemical differences in cellulose, hemicellulose, lignin, and extractives between heartwood and sapwood (Ma *et al.* 2022). Analyzing these differences provides valuable insights for elucidating the mechanisms underlying heartwood formation and is crucial for understanding wood properties and tailoring utilization strategies. Lesser-studied hardwood species are increasingly investigated for their chemical profiles to assess their potential for material and non-timber applications. For instance, studies on *Allanthus altissima* and *Albizia julibrissin* have detailed the variability in chemical components (extractives, lignin, holocellulose, ash) between wood and bark, as well as across different radial positions and tree ages, linking these compositions to potential uses in biofuels, composites, and pharmaceuticals (Ghavidel *et al.* 2022; Terzopoulou and Kamperidou 2022).

Erythrophleum fordii, commonly known as “ironwood,” is a tree species belonging to the genus *Erythrophleum* within the Fabaceae family (Yang *et al.* 2017). The species is naturally distributed in southern China, central and northern Vietnam, and parts of Laos (16°~24°N, 108°~118°E), roughly extending in a belt-shaped pattern along the Tropic of Cancer (Yang *et al.* 2017). It is characterized by its high density (0.85 g/cm^3), exceptional strength with a compressive strength of 68 MPa and a bending strength of 142 MPa, and a high Janka hardness of approximately 2500 lbf (Fang and Fang 2007). Its outstanding durability is historically evidenced by its use in ancient Chinese shipbuilding and centuries-old wooden structures such as the Zhenwu Pavilion (built in 1573). These properties, coupled with its distinctive grain pattern—appreciated in Chinese fine furniture-making since the Ming and Qing dynasties (1368-1912)—establish it as a premium material for high-end furniture, shipbuilding, and artistic carving (Fang and Fang 2007; Lin *et al.* 2015). The current market price is approximately 1400 USD per cubic meter. Additionally, its seeds and bark possess medicinal properties, traditionally used to “boost Qi and activate blood circulation (Son 2019; Chen *et al.* 2022).” Ecologically, *E. fordii* not only exhibits strong nitrogen-fixing capacity, making it an ideal companion species in eucalyptus mixed forests, but it also serves to improve pure coniferous plantations (*e.g.*, *Pinus massoniana*, *Cunninghamia lanceolata*) and enhance forest land productivity (Li *et al.* 2023; Hu *et al.* 2025; Huang *et al.* 2025). It also demonstrates potential for application in the remediation of contaminated soils (Chen *et al.* 2024). Collectively, *E. fordii* holds significant economic and ecological value. However, rigorous research on its fundamental wood chemical composition is lacking. This knowledge gap not only hinders a scientific understanding of the basis for its superior wood properties (*e.g.*, hardness and durability) but also obscures its potential for valorization as a source of non-timber forest products, particularly pharmaceutical raw materials derived from its heartwood. Filling this gap is essential for promoting the scientific cultivation, high-value utilization, and sustainable management of this valuable species.

To address this gap, this study systematically analyzed the chemical constituents, namely cellulose, hemicellulose, lignin, and extractives, in the heartwood and sapwood of *E. fordii*. The work aimed to (1) characterize and compare the chemical profiles of heartwood and sapwood using a suite of standardized and complementary analytical techniques; (2) elucidate the key chemical disparities between the two tissues, with a focus on bioactive extractives; (3) provide a theoretical foundation for the high-value utilization of *E. fordii* resources, particularly highlighting the potential of heartwood as a source of functional natural products; and (4) contribute scientific data to the understanding of heartwood formation mechanisms in hardwood species.

EXPERIMENTAL

Test Material

The study materials were obtained from an 18-year-old managed plantation of *E. fordii* located in Pingxiang, Guangxi, China (approximately 22°13' N, 106°43' E, at an altitude of 220 m). The region experiences a subtropical monsoon climate with a mean annual temperature of approximately 22 °C and an annual precipitation of around 1300 mm. The sampled stand received conventional silvicultural management.

Three trees were felled, and a 5-cm-thick disc was collected at breast height (1.3 m above ground) from each one. The discs had an average diameter of 17.3 ± 1.8 cm, heartwood width of 8.7 ± 1.6 cm, and annual ring width of 0.39 ± 0.08 cm. The sampled trees were 18 years old, which is beyond the typical juvenile wood phase for this species, thus ensuring that the chemical compositions analyzed are representative of mature heartwood and sapwood. They were transported to the laboratory, air-dried, and ground into powder using a mill. The fraction passing through 40 to 60 mesh sieves was collected for subsequent chemical analysis.

Determination of Chemical Composition

The contents of cellulose, hemicellulose, and lignin were determined using established methods (Velázquez-De Lucio *et al.* 2020). Briefly, 1 g of wood flour was boiled in a neutral detergent solution containing sodium sulfite and thermostable α-amylase to obtain neutral detergent fiber (NDF). The resulting residue was then boiled in an acid detergent solution to yield acid detergent fiber (ADF). The ADF residue was then treated with 72% H_2SO_4, and the ash content was corrected for to determine acid detergent lignin (ADL). The content of each component was calculated by mass difference as follows: hemicellulose content = NDF - ADF, and cellulose content = ADF - ADL.

The contents of various extractives, moisture, and pH were determined using established methods (Qiu *et al.* 2019). The cold-water extract was obtained by extracting 2 g of wood flour with 300 mL of distilled water (23 °C) for 48 h. The hot water and 1% NaOH extracts were obtained by extracting 2 g of wood flour with 200 mL of boiling water (100 °C) and 100 mL of 1% NaOH solution, respectively, in a boiling water bath for 3 h and 1 h. The benzene-alcohol extract was obtained *via* Soxhlet extraction of 3 g of wood flour with 150 mL of benzene-alcohol (2:1, v/v) for 6 h. The moisture content was determined by drying 3 g of the sample at 105 °C to a constant weight. The pH was measured on a mixture of 3 g of wood flour and 30 mL of CO_2-free water after 45 min of standing.

All experiments were performed with three biological replicates and two technical replicates per biological replicate.

FTIR analysis

The wood flour was dried and sieved through a 200-mesh screen. Subsequently, 1–2 mg of the sample was thoroughly mixed with 0.1 g of KBr and pressed into a pellet for FTIR analysis (VERTEX 70, Bruker Corporation, Germany). The spectra were acquired under the following conditions: a wavenumber range of 4000 to 500 cm^{-1}, 32 cumulative scans, an optical path difference (OPD) velocity of 0.2 cm/s, and a resolution of 4 cm^{-1}. The spectral interference from KBr was subtracted in real-time during data acquisition.

Total Phenolic and Flavonoid Content

The contents of total phenolics and flavonoids in the benzene-alcohol extract were determined with slight modifications to a reported method (Chen *et al.* 2025). Specifically, the total phenolic content was analyzed using the Folin-Ciocalteu assay. Briefly, 2.5 mL of the sample was mixed with 1 mL of Folin-Ciocalteu reagent, followed by the addition of 2 mL of a 15% sodium carbonate (Na_2CO_3) solution. After a 90-min reaction in the dark, the absorbance was measured at 760 nm using a UV spectrophotometer (UV-2600i, Shimadzu, Japan), with gallic acid as the standard.

A 0.5 mL aliquot of the sample was mixed with 0.5 mL of 5% $NaNO_2$ for 6 min. Then, 0.5 mL of $Al(NO_3)_3$ was added. The mixture was vortexed and allowed to stand for 6 min. Subsequently, 4 mL of 4% sodium hydroxide (NaOH) was added, and the mixture reacted for 15 minutes before the absorbance was measured at 510 nm. Rutin was used as the standard for quantification.

Chemical Composition Analysis of Extracts

The benzene-alcohol extract was dissolved in 2 mL of methanol, and the resulting solution was analyzed using a Gas Chromatography-Mass Spectrometry system (GC-MS, 5975C, Agilent Technologies, USA) equipped with a triple quadrupole mass analyzer. The MS conditions were as follows: Scan mode: Full scan; Mass scan range: 30 to 700 *m*/*z*; Ion source: Electron Impact (EI); Ion source temperature: 300 °C; Injection mode: Splittless; Injector temperature: 280 °C; Carrier gas: High-purity helium; Solvent delay: 3 min. GC conditions: Capillary column: TG-5SILMS (30 m × 0.25 mm × 0.25 μm); Column flow rate: 1.0 mL/min; Injection volume: 1 μL; Oven temperature program: The initial temperature was held at 50 °C for 1 min, then ramped to 120 °C at a rate of 10 °C/min, followed by a further increase to 280 °C at a rate of 2 °C/min, and finally held at 280 °C for 5 min.

Data Processing

All experiments were conducted in triplicate. Statistical analyses, including analysis of variance (ANOVA), least significant difference (LSD) test, and principal component analysis (PCA), were performed using WPS Office 2023 and OriginPro 2024 software.

RESULTS AND DISCUSSION

Chemical Composition of *E. fordii* Wood

A comparative analysis of the primary chemical components and pH values in the heartwood and sapwood of *E. fordii* is presented in Table 1. The results indicate a notable divergence in chemical composition content between the two tissue types.

The cellulose, hemicellulose, and lignin contents were 13.15%, 21.08%, and 6.10% higher in the sapwood than in the heartwood, respectively. This pattern is consistent with that reported for *C. lanceolata* (Qin *et al.* 2004). In the pulp and paper industry, the cellulose content of a raw material is generally considered a key factor determining pulp quality and yield. The cellulose content in *E. fordii* sapwood reached 49.9%, which is comparable to or even surpasses that of some established pulpwood species. For instance, it exceeded the reported cellulose content of *Eucalyptus viminalis* (a high-quality raw material for papermaking) in some studies, indicating its potential application value in the production of high-grade paper products such as calligraphy and painting paper (Wang *et al.* 2018). The lignin content of *E. fordii* (28.6 to 30.4%) is higher than that reported for many common hardwoods and is comparable to several prized rosewood species. For example, it is higher than that of *Dalbergia cochinchinensis*, *Dalbergia oliveri*, *Dalbergia granadillo*, and *Pterocarpus macrocarpus*, and falls within the range reported for *Dalbergia odorifera* and *Pterocarpus santalinus* (Liu *et al.* 2015). This elevated lignin content likely contributes to its high density and mechanical strength, suggesting that *E. fordii* may share similar durability-related wood properties with these precious timbers.

Ash in wood primarily consists of inorganic substances such as salts and metal oxides, and its content directly reflects the enrichment level of inorganic components. The ash content was higher in the heartwood than in the sapwood, indicating a greater accumulation of inorganic constituents (*e.g.*, calcium, potassium, silica) during heartwood formation. This accumulation may contribute to the higher density and hardness characteristic of the heartwood, as inorganic deposits can fill cell lumens and cell walls. Regarding moisture content, a significant difference was observed between the heartwood and sapwood. The moisture content was significantly higher in the heartwood (103.0%) than in the sapwood (66.0%). This substantial disparity is likely related to physiological changes during heartwood formation, including the loss of living parenchyma cells and changes in cell wall porosity and pit aspiration, which can trap water differently. The high heartwood moisture content, despite its commonly perceived lower permeability, warrants further investigation into its microstructure and water-binding mechanisms. Furthermore, both the sapwood and heartwood of *E. fordii* were weakly acidic, but the heartwood was more acidic. This increased acidity is a common feature in heartwood and is generally attributed to the accumulation of greater quantities of acidic extractives, such as phenolics and organic acids, during heartwood formation (Qiu *et al.* 2019).

The extractive contents, including cold-water, hot-water, 1% NaOH, and benzene-ethanol extractives, were all higher in the heartwood than in the sapwood. This pronounced enrichment confirms that heartwood is the primary repository for extractives in *E. fordii*. Microscopic images (Fig.1) show that yellow heartwood substances are deposited in the vessels of the heartwood, while no such deposits were observed in the sapwood vessels (indicated by arrows). The extraction rates for cold-water and hot-water methods were significantly lower than those of the other two methods. This is likely because water can only dissolve small amounts of substances such as tannins, pigments, and inorganic salts, which are present in relatively low concentrations in wood. In contrast, the 1% NaOH method yielded substantially higher extractives than the other three methods. This is because 1% NaOH dissolves not only the aforementioned substances but also lignin, hemicellulose fractions, proteins, and amino acids. Wood extractives not only influence properties such as color, odor, dimensional stability, and decay resistance but also affect the processing characteristics of wood. They are a major factor determining the value of wood, particularly in precious wood species. The most significant difference between heartwood and sapwood is often their extractives content.

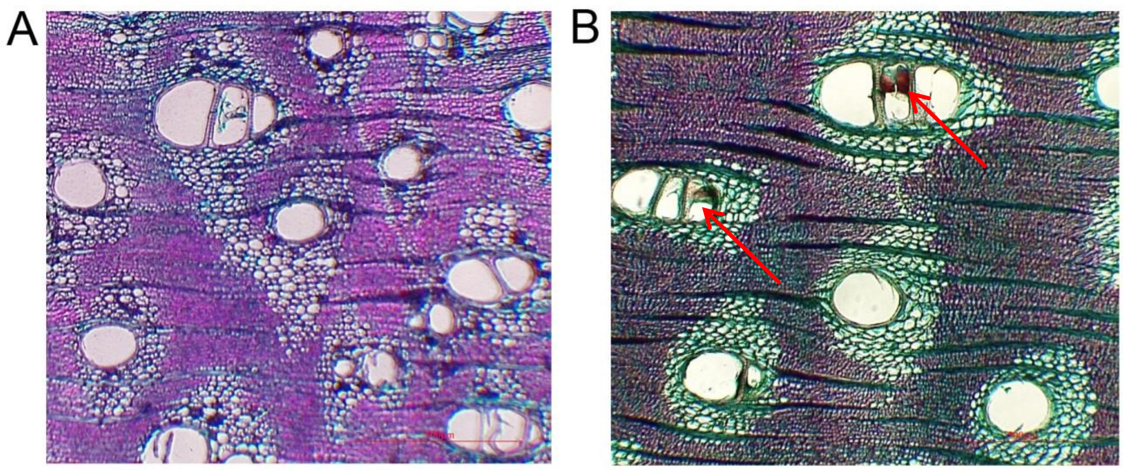

Fig. 1. Microscopic photos of sapwood (A) and heartwood (B)

Table 1. Chemical Components of Woods

	Sapwood	Heartwood
Cellulose (%)	49.89 ± 0.71a	44.10 ± 1.08b
Hemicellulose (%)	14.67 ± 0.47a	12.11 ± 1.01b
Lignin (%)	30.38 ± 1.39a	28.63 ± 1.65b
Ash (%)	2.02 ± 0.09b	2.50 ± 0.23a
Cold Water extractives (%)	6.81 ± 0.62b	8.82 ± 0.49a
Hot Water extractives (%)	12.11 ± 0.49b	17.82 ± 0.58a
1% NaOH extractives (%)	24.54 ± 0.89b	34.36 ± 1.97a
Benzene-alcohol extractives (%)	4.40 ± 0.32b	14.09 ± 0.29a
Moisture (%)	66.05 ± 8.71b	102.95 ± 8.27a
pH	5.56 ± 0.01a	5.14 ± 0.00b

Changes in Lignin

FTIR analysis indicated that the lignin structures in sapwood and heartwood were fundamentally similar, sharing major characteristic peaks and differing primarily in the intensities of certain absorbance bands (Fig. 2A). This suggests that the core chemical structure of lignin remained largely unchanged during the transition from sapwood to heartwood. Nevertheless, PCA clearly separated the sapwood and heartwood sample groups (Fig. 2B), a distinction attributable mainly to differences in peak intensities rather than to fundamental structural alterations. The assignments of the major absorption peaks are as follows: 3340 cm⁻¹ (O–H stretching vibration); 2903 cm⁻¹ (C–H stretching vibration of methyl and methylene groups); 1736 cm⁻¹ (C=O stretching vibration of non-conjugated carbonyl groups); 1640 cm⁻¹ (C=O stretching vibration of conjugated carbonyl groups); 1592 cm⁻¹ and 1506 cm⁻¹ (aromatic skeleton vibrations), with the 1592 cm⁻¹ band also containing a contribution from C=O stretching); 1455 cm⁻¹ (C–H bending vibration of methyl or methylene groups); 1420 cm⁻¹ (a combination of aromatic skeleton vibration and C–H in-plane bending); 1368 cm⁻¹ (O–H in-plane bending of phenolic groups and aromatic C–O stretching); 1325 cm⁻¹ and 1100 cm⁻¹ (C–O vibrations in syringyl units); 1260 cm⁻¹ (C–O vibration in guaiacyl units); 1230 cm⁻¹ and 1155 cm⁻¹ (C–O and C–O–O vibrations, respectively); 1030 cm⁻¹ (aromatic C–H in-plane deformation vibration); 898 cm⁻¹ (C1–H out-of-plane bending vibration of the β-glycosidic linkage in cellulose); and 830 cm⁻¹ (aromatic C–H out-of-plane bending vibration in lignin) (Yang *et al.* 2016; Xiao *et al.* 2019; Ren *et al.* 2023).

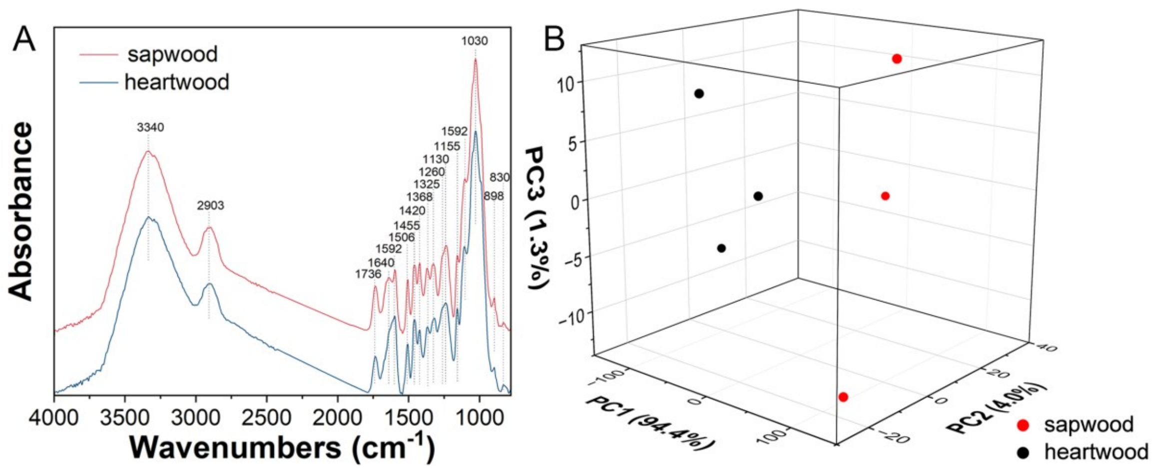

Fig. 2. FTIR spectrum (A) and PCA (B) analysis of *E. fordii*

The characteristic absorbances of lignin were primarily observed at 1592, 1506, 1420, and 1368 cm⁻¹. The strong absorbances at 1325, 1100, and 830 cm⁻¹ indicated the presence of syringyl (S) units, while the weak absorbance at 1260 cm⁻¹ corresponded to guaiacyl (G) units (Qiu *et al.* 2019). This pattern demonstrates that the lignins in both the sapwood and heartwood of *E. fordii* are of the SG-type, with syringyl units being predominant. The relative peak intensity at 1640 cm⁻¹ (conjugated C=O) was lower in the heartwood than in the sapwood. This may be attributed to a shift in the spectral contribution towards the typical aromatic vibration at 1592 cm⁻¹, possibly due to a higher degree of condensation in the heartwood lignin, which reduces the proportion of conjugated carbonyl structures (Ren *et al.* 2023). Furthermore, the enhanced absorbance at 1592 cm⁻¹ in the heartwood might be associated with the accumulation of extractives during heartwood formation (Feng *et al.* 2025).

Compared to the sapwood, the heartwood exhibited a decrease in the intensity of the characteristic lignin peaks at 1420 cm⁻¹ and 1368 cm⁻¹. This suggests a relative decrease in the characteristic vibrational modes associated with lignin in the heartwood fiber cell walls, which could be related to masking by accumulated extractives or subtle changes in lignin-carbohydrate complex associations. It may also indicate a slightly lower relative degree of lignification in the heartwood fibers compared to the sapwood, which underwent more complete lignification during active growth (Ren *et al.* 2023). This finding is consistent with the results from the lignin content determination. The weakened absorbance at 1736 cm^{-1} reflects a decrease in hemicellulose content during the heartwood transformation, aligning with the previous chemical composition analysis (Xiao *et al.* 2019, 2020). The stronger absorbance at 898 cm^{-1} in the sapwood indicates a higher proportion of the amorphous region in its cellulose. This could be because the greater lignin content in the sapwood requires more amorphous regions to facilitate hydrogen-bonding connections (Zhou *et al.* 2018).

Total Phenolic and Total Flavonoid Contents

Polyphenols in natural products are closely linked to human health due to their diverse biological activities, such as anti-inflammatory and anti-tumor effects. Flavonoids, as an important class of plant secondary metabolites, not only play extensive roles in plant growth, development, and stress resistance but also exhibit significant bioactivities (Chen *et al.* 2023). Therefore, determining the contents of polyphenols and flavonoids in plant materials is of considerable importance. Figure 3 shows that the total phenolic contents in the sapwood and heartwood of *E. fordii* were 3.74 mg GAE/g DW and 19.86 mg GAE/g DW, respectively, while the total flavonoid contents were 5.34 mg RE/g DW and 36.47 mg RE/g DW, respectively. The heartwood contained 4.3 and 5.6 times the amount of polyphenols and flavonoids found in the sapwood, indicating a substantial enrichment of these compounds in the heartwood. This enrichment indicates that heartwood serves as a storage site for secondary metabolites, which enhance its decay resistance, durability, and dimensional stability, thereby increasing its overall value. It is particularly noteworthy that the flavonoid content in the heartwood of *E. fordii* was even higher than that in the precious wood *D. odorifera* (Ma *et al.* 2020). These findings, along with its abundant polyphenolic constituents, suggest that *E. fordii* heartwood has considerable potential as a rich source of natural antioxidants and for developing functional natural products aimed at promoting health.

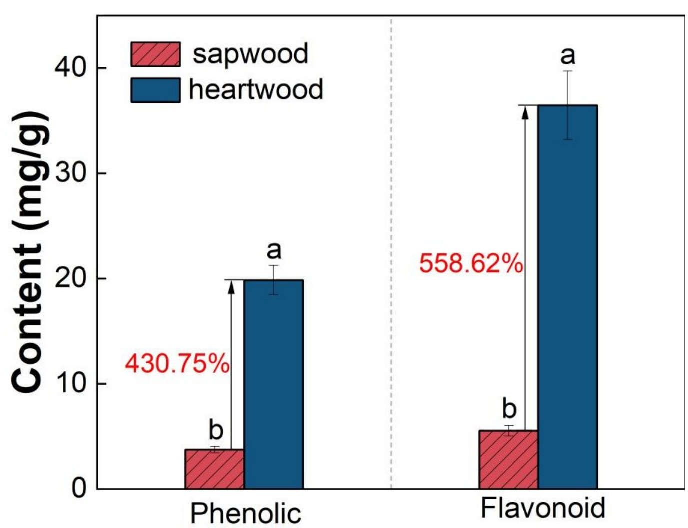

Fig. 3. Total phenolic and total flavonoid contents

Analysis of Components of Extractives

The benzene-alcohol extractives from *E. fordii* wood were analyzed using GC-MS. Compound identification was performed by comparing mass spectra with the NIST17.L database, and the relative percentage content of each compound was calculated by area normalization method. As shown in Table 2 and Fig. 4, a total of 15 compounds were identified, encompassing 6 aliphatic compounds, 4 aromatic compounds, 3 phytosterols, 1 terpenoid and 1 fat-soluble vitamin. Among these, 14 compounds were detected in the heartwood and 11 in the sapwood. Although a few components were exclusive to the heartwood, the sapwood contained most of the compounds found in the heartwood.

Table 2. Composition of Extractives from *E. fordii* Wood

No.	Retention Time	Name	Relative Content (Area %)	
			Sapwood	Heartwood
1	11.69	Resorcine	-	0.20%
2	14.20	1-Tetradecene	-	0.28%
3	14.50	Pyrogallol	-	3.90%
4	21.91	1-Hexadecene	-	0.51%
5	38.70	Butyl isobutyl phthalate	0.92%	1.69%
6	39.02	Palmitic acid	7.22%	4.39%
7	46.47	Linoleic acid	5.48%	3.68%
8	46.71	Elaidinic acid	7.72%	2.04%
9	57.79	2,2'-Methylenebis(6-tert-butyl-4-methylphenol)	0.90%	0.78%
10	71.61	Erucylamide	4.14%	5.30%
11	83.12	Vitamin E	0.53%	2.60%
12	85.39	Campesterol	3.65%	10.63%
13	86.41	Stigmasterol	5.97%	12.96%
14	88.16	β-Sitosterol	13.10%	22.82%
15	92.08	Stigmast-4-en-3-one	2.75%	-

Note: “-” means not detected.

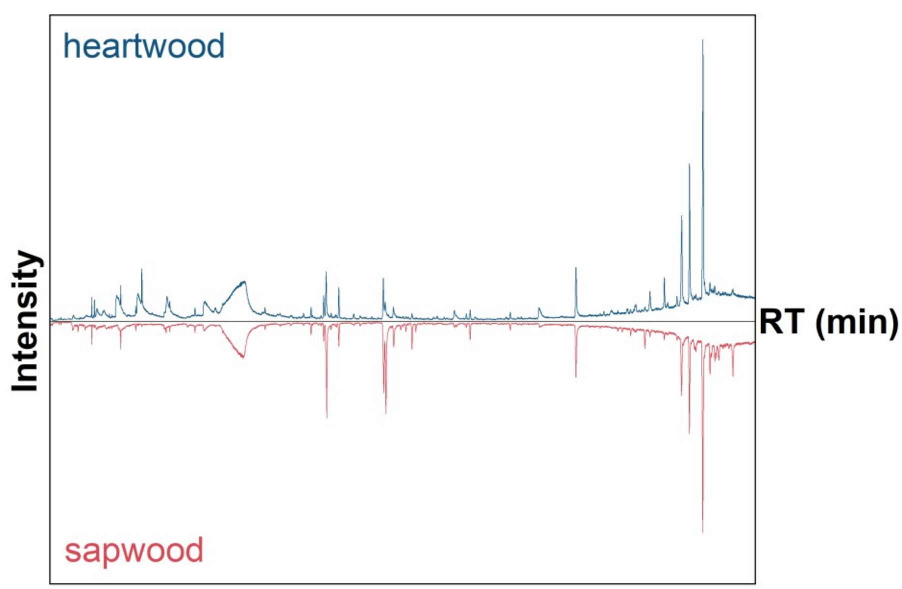

Fig. 4. GC-MS chromatograms of *E. fordii*

The most abundant component in both sapwood and heartwood extractives was β-sitosterol, a compound with reported physiological activities, including effects against lymph node tuberculosis, goiter, and depression (Kim *et al.* 2015; Wen *et al.* 2016; Zhao *et al.* 2016). Fatty acids were relatively more abundant in the sapwood, with the contents of palmitic acid, linoleic acid, and elaidinic acid all being higher than those in the heartwood. Among them, palmitic acid exhibits anti-tumor activity, while linoleic acid is reported to enhance immunity and promote metabolism (Ji *et al.* 2013; Hsiao *et al.* 2014; Wang *et al.* 2023). The heartwood contained a greater diversity of phytosterol and fat-soluble vitamin, including Vitamin E, campasterol, stigmasterol, and β-sitosterol. Vitamin E possesses strong antioxidant capacity, whereas campasterol and stigmasterol can inhibit cholesterol absorption (Brzeska *et al.* 2016; Traber 2021; Bakrim *et al.* 2022). Furthermore, stigmasterol serves as an important raw material in the pharmaceutical industry (Brzeska *et al.* 2016). The collective enrichment of these bioactive sterols and Vitamin E in the heartwood aligns with its high total phenolic and flavonoid content, painting a consistent picture of the heartwood as a concentrated source of compounds with antioxidant, anti-inflammatory, and potential cholesterol-modulating properties. Stigmast-4-en-3-one, detected in the sapwood, is an oxidation product of stigmasterol. Its absence in the heartwood may be due to the stronger antioxidant capacity of the heartwood extractives, which may have suppressed this oxidation.

It is noteworthy that compared to traditional precious wood species such as *D. odorifera* and *P. santalinus* (Jiang *et al.* 2020; Zhao *et al.* 2020), the heartwood of *E. fordii* exhibits a significantly lower diversity of volatile components. This chemical profile difference is crucial. The scarcity of volatile aromatic compounds likely explains why, despite its attractive brown color, *E. fordii* heartwood lacks the distinctive and prized aroma characteristic of many traditional hongmu timbers. Concurrently, although *E. fordii* shares similarities with precious hardwoods in terms of heartwood density and some chemical properties, the deficiency in volatile constituents also leads to a less pronounced oily appearance. These sensory characteristics (aroma and oily feel) are highly valued in the classical Chinese hongmu aesthetic and functional evaluation. Therefore, this deficiency in volatile and oleoresin components could be a key reason why *E. fordii*, despite its excellent mechanical properties and durability, is not listed in the Chinese National Standard "Hongmu" (GB/T 18107-2017).

CONCLUSIONS

1. The sapwood of *E. fordii* exhibited higher cellulose, hemicellulose, and lignin contents, while the heartwood had higher ash and extractive contents. Both sapwood and heartwood were weakly acidic, with the heartwood being more acidic.
2. Fourier transform infrared (FT-IR) analysis indicated that the fundamental lignin structure was largely consistent between the sapwood and heartwood, characterized by similar spectral features and only minor differences in absorption intensities. The lignin in both tissues was identified as SG-type, with syringyl units being predominant, suggesting that the core lignin structure remained stable during heartwood formation.
3. The heartwood was the primary site for accumulating bioactive constituents, with total phenolic and flavonoid contents 4.3 and 5.6 times higher than those in the sapwood, respectively. Notably, the flavonoid content even surpassed that of the traditional

precious wood *D. odorifera*. Gas chromatography – mass spectrometry (GC-MS) analysis further revealed that the heartwood was rich in terpenoids and sterols, such as Vitamin E, stigmasterol, and β-sitosterol, which are known for their antioxidant, cholesterol-lowering, and pharmaceutical properties. This chemical profile underscores the significant potential of *E. fordii* heartwood in the development of functional natural products and as a source of pharmaceutical raw materials, though further biological experiments are required to validate its efficacy.

4. Despite the similarities in density and some chemical properties between *E. fordii* heartwood and precious hongmu timbers, its extractives contained a significantly lower diversity of volatile compounds. This deficiency likely accounts for its lack of a distinct aroma and oily appearance. The absence of these desirable sensory characteristics may be a crucial reason why *E. fordii*, despite its excellent wood properties, is not listed in the Chinese National Standard for Hongmu (GB/T 18107-2017).

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Use of Generative AI

In the preparation of this manuscript, the AI tool Deepseek was used solely to polish the English language of the translated text.

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