Timber Species Identification and Selection Principles of Wooden Components in the Sunjialou Cultural Relic Building, Nanyang City

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Abstract

To support the scientific restoration and replacement of wooden components in the Sunjialou Cultural Relic Building (Nanyang City), optical microscopy was employed to identify the timber species of key structural elements, including columns, beams, purlins, rafters, and door/window assemblies. The results are as follows: (1) The identified timbers represent 4 families and 5 taxonomic groups: *Larix* sect. *Multiseriales* (Pinaceae), *Pinus* sect. *Cembra* (Pinaceae), *Cunninghamia lanceolata* (Taxodiaceae), *Quercus* sect. *Cerris* (Fagaceae), and *Ulmus* sect. *Madocarpus* (Ulmaceae). (2) The timber selection for the wooden components exhibits dual characteristics of "functional adaptation and regional resource dependence": High-strength hardwoods (Quercus sect. Cerris and Ulmus sect. Madocarpus) were utilized for core load-bearing components (columns and beams); decay-resistant softwoods (Larix sect. Multiseriales and Cunninghamia lanceolata) for secondary load-bearing components (purlins and rafters); and easily workable softwoods (Pinus sect. Cembra) for non-load-bearing/decorative components (doors and windows). Except for Larix sect. Multiseriales, which was sourced from the adjacent Qinling Mountains, the other four groups are native to or widely cultivated in Nanyang City or southwestern Henan Province, aligning with the principle of “local or near-source material utilization”. The research findings systematically reveal, for the first time, the material selection characteristics of Sunjialou’s Ming–Qing dynasty architecture, confirming the traditional construction wisdom of “function-oriented material selection”. Simultaneously, this study provides a scientific basis for the precise restoration and replacement of wooden components in the Sunjialou Cultural Relic Building (e.g., material selection for the replacement of decayed components) and serves as a representative case for research on the timber species database and traditional construction techniques of Ming–Qing ancient architecture in southwestern Henan Province.

1. Introduction

As material carriers of regional historical and cultural heritage, the timber selection for the wooden frames of ancient buildings not only embodies the traditional craftsmanship wisdom of “material-property adaptation” but also reflects the resource utilization patterns and socio-economic contexts of specific eras—making it a pivotal focus in cultural heritage protection research. Located in the transitional zone between the Central Plains and Southern China, Nanyang developed a residential system integrating the regular layout of the Central Plains with adaptations to southern climatic conditions from the Ming and Qing dynasties to the modern period. The preserved wooden structures not only serve as critical tangible evidence for investigating the modern architectural history of the Central Plains but also act as repositories of diverse historical memories, including red culture and commercial heritage.

The Sunjialou Cultural Relic Building, situated east of the intersection of Jiefang Road and Minzhu Street in central Nanyang (33°01'N, 112°33'E), is a typical representative of such relics in the ancient city. First constructed during the Guangxu period of the Qing Dynasty (1875–1908), it was designated a Nanyang municipal-level cultural heritage site in 2002. Currently, the site comprises two courtyards: Courtyard No.

1 (former residence of Yao Shiyi, president of the Nanyang Chamber of Commerce during the Republic of China, which witnesses the city's modern commercial development) and Courtyard No. 2 (former site of the Central County Party Committee of the Communist Party of China in Nanyang and the ancestral home of revolutionary martyrs Cao Yunge and Cao Jianming, which embodies Nanyang's red history). Architecturally, Sunjialou features a "shop in the front, residence at the back" and "single-entry multi-courtyard" spatial layout, combined with a brick-wood composite structure—reflecting the construction logic of "li-long residences" (narrow alleyway residences) in southwestern Henan. Its wooden frame serves as the core load-bearing system, while blue bricks, gray tiles, and wall designs are adapted to Nanyang's subtropical monsoon climate (hot and rainy summers, dry and cold winters). Crafts such as door/window wood carvings and beam/column reliefs further enhance its historical and artistic value.

However, following a century of natural weathering and environmental deterioration, the Sunjialou Cultural Relic Building faces severe preservation challenges. Although the main structure remains relatively intact, the wooden components of the core load-bearing system have undergone significant deterioration, posing substantial threats to the building's structural integrity. On-site investigations (Figs. 1) revealed varying degrees of deterioration in key wooden components (column bases, eave rafters, and eave purlins), primarily concentrated in moisture-prone zones. Decayed wood displays color transitions from light yellow to brown or black, with a brittle and crumbly texture; some components even crumble upon contact, directly compromising the structural load-bearing capacity. Insect-infested components feature dense circular holes (1–3 mm in diameter) on the surface and crisscrossing internal tunnels. Such deterioration not only impairs component integrity but also endangers the building's overall structural safety. Without targeted protection, irreversible loss of historical information will occur.

The restoration of ancient wooden components must strictly comply with the principles of "authenticity" and "minimum intervention", and accurate timber species identification constitutes a fundamental prerequisite. Timber species exhibit significant variations in density, mechanical strength, decay resistance, and workability (e.g., *Quercus* sect. *Cerris* exhibits high strength but is susceptible to insect infestation, while *Cunninghamia lanceolata* offers good decay resistance but has fragile sapwood). The use of inappropriate species can result in poor compatibility between the restored components and the original structure, accelerating aging. Additionally, tracing timber sources via species identification enables the reconstruction of Nanyang's modern construction supply chain and resource utilization patterns, filling the research gaps in traditional construction techniques in southwestern Henan.

Limited studies have systematically examined the timber species and their selection mechanisms for modern-era ancient buildings in this region, which features distinct north-south cultural and climatic transitions. To address this research gap, the present study focuses on the wooden components of the Sunjialou Cultural Relic Building, with a focus on key load-bearing components (columns, beams, purlins, rafters). Optical microscopy was employed to observe the anatomical characteristics of the wood samples, and timber species were identified in line with international and domestic wood taxonomic standards. The objectives are to elucidate the composition of timber species of the building's original wooden components, uncover the underlying principles of timber selection, provide scientific basis for subsequent restoration and protection efforts, and offer a reference for similar studies on wooden components of heritage buildings.

2. Materials and Methods

2.1 Materials

2.1.1 Sampling Objects and Location

Sampling was performed on wooden components with different functional roles from the Sunjialou Cultural Relic Building, including: (1) core load-bearing components (columns for vertical load transmission and beams for horizontal load distribution); (2) secondary load-bearing components (purlins connecting beams and rafters, and rafters supporting the roof structure); and (3) non-load-bearing components (doors and windows).

2.1.2 Sampling Principles and Methods

Sampling strictly adhered to the “minimum intervention” principle for cultural heritage protection to minimize additional damage to the building. An increment borer (Model: 10–100–1027; Manufacturer: Haglöf AB, Sweden) was utilized for non-destructive or micro-destructive sampling. Sampling locations were prioritized in areas with evident deterioration but no adverse impact on the core load-bearing capacity, including column bases (moisture-prone decayed zones), beam ends (joint connection zones), eave purlin ends (exposed weathering zones), and eave rafter tips (moisture-prone decayed zones). A total of 18 valid samples were collected, with specific sampling information detailed in Table 1.

Table 1
The sampling information of wooden components

Sample No.	Sampling Location	Sample No.	Sampling Location
No.1	Wooden column	No.10	Wooden column
No.2	Eave rafter	No.11	Eave rafter
No.3	Door/window	No.12	Eave rafter
No.4	Eave rafter	No.13	Eave rafter
No.5	Eave purlin	No.14	Wooden column
No.6	Eave rafter	No.15	Door/window
No.7	Eave purlin	No.16	Wooden column
No.8	Eave rafter	No.17	Wooden beam
No.9	Eave purlin	No.18	Wooden beam

2.2 Methods

2.2.1 Embedding Pretreatment of Samples

To address severe decay (e.g., crumbly texture, fragmented structure) or insect infestation (e.g., dense internal tunnels, compromised integrity) in some samples, a polyethylene glycol (PEG) chemical consolidation method for decayed wooden components of ancient buildings [1–2] was employed. A three-step process—vacuum degassing – gradient PEG impregnation – shaping and embedding"—was adopted to consolidate the samples, providing structural support for subsequent section preparation:

Vacuum degassing

Samples were placed in a vacuum desiccator, and a vacuum was applied until the samples were fully submerged (to remove air from the wood pores and promote the penetration of the impregnation solution). After turning off the vacuum pump, the samples were allowed to stand for 30 min.

Gradient PEG impregnation: Samples were sequentially immersed in aqueous PEG solutions (molecular weight: 2000) with mass concentrations of 20%, 40%, 60%, 80%, and 100%. Each concentration was incubated in a constant-temperature oven at 60°C for no less than 48 h; the 100% PEG solution was applied twice to ensure complete filling of the wood cell wall pores.

Embedding

The cutting surface of each sample was fixed facing downward at the bottom of a stainless steel embedding mold. Molten 100% PEG (at 60°C) was poured into the mold, and a plastic embedding box was immediately covered to prevent air bubble formation. After natural cooling and solidification, a solid block tightly bonded to the sample was formed to prevent sample fragmentation during sectioning.

2.2.2 Preparation of Sample Sections

Wood sections were prepared in accordance with the national standard *"General Method of Wood Identification"* [3] and the wood sectioning techniques reported by Yang et al. [4–5]:

Sectioning

Embedded samples were mounted on the stage of a Leica HistoCore AUTOCUT microtome (Leica Microsystems, Germany). Transverse, radial, and tangential sections (10–15 μm in thickness) were prepared.

Gradient dehydration

Sections were sequentially immersed in 50%, 75%, 95%, and 100% ethanol aqueous solutions for 10 min per step to gradually remove moisture, thereby preventing tissue wrinkling during subsequent degreasing and mounting.

Degreasing and clearing

Dehydrated sections were immersed in xylene for 3–5 min to remove grease and improve transparency, enhancing the clarity of microscopic observation.

Mounting and preservation

Neutral resin was applied to clean glass slides, and the degreased sections were uniformly spread on the resin surface. A coverslip was carefully placed to prevent air bubble entrapment, and slides were air-dried in a well-ventilated environment. Permanent sections were obtained following complete resin curing.

2.2.3 Observation and Identification of Timber Species

Microscopic observation

Permanent sections were examined under a Nikon ECLIPSE Ni-U biological microscope (Nikon Corporation, Japan) at magnifications of 4×, 10×, 20×, and 40×. The anatomical characteristics of the transverse, radial, and tangential sections were documented, and microscopic images were captured.

Basis of timber species identification: The identification was based on authoritative international and domestic wood anatomical standards and literature, including: *IAWA List of Microscopic Features for Softwood Identification* [6] and *IAWA List of Microscopic Features for Hardwood Identification* [7] issued by the International Association of Wood Anatomists (IAWA); *Atlas of Chinese Woods* [8], which systematically compiles anatomical characteristics, distribution, and uses of native Chinese tree species; *Names of Chinese Main Woods* [9], which standardizes the naming and classification of major domestic timber species.

Process of timber species identification

For softwoods, key characteristics included growth ring distinctness, tracheid properties (gradual or abrupt transition from earlywood to latewood, presence or absence of spiral thickenings, type of bordered pittings on radial walls), type of resin canals (presence or absence, axial or radial), and ray cell morphology (presence or absence of ray tracheids, serrations on the inner walls of ray tracheids, type of cross-field pittings). For hardwoods, key characteristics included growth ring distinctness, vessel properties (distribution, arrangement, grouping pattern, type of perforation plates, type of intervessel pitting, presence or absence of spiral thickenings), type of axial parenchyma (apotracheal or paratracheal), type of wood fibers, type of wood rays (homocellular or heterocellular), and presence or absence of gum canals. The observed characteristics were compared with those documented in the aforementioned standards, literature, and type specimens to determine the timber species.

3. Results and Discussion

Microscopic anatomical observation and comparative analysis of 18 wooden component samples (covering columns, beams, purlins, rafters, and doors/windows) revealed that the timber species used in the Sunjialou Cultural Relic Building belong to 5 taxonomic groups, 5 genera, and 4 families (Pinaceae, Taxodiaceae, Fagaceae, Ulmaceae) (Table 2). The anatomical characteristics, identification results, and adaptability to building construction are discussed below:

Table 2
Identification results of timber species

Wood Category	Sample No.	Family	Genus	Section	Species
Class I	No.2, No.4, No.5, No.6, No.7, No.9, No.11, No.13	Pinaceae	*Larix*	sect. *Multiseriales*	*L. chinensis*, *L. mastersiana*, *L. potaninii*, *L. potaninii* var. *macrocarpa*, *L. speciosa.*
Class II	No.3, No.15		*Pinus*	sect. *Cembra*	*P. armandii*
Class III	No.8, No.12	Taxodiaceae	*Cunninghamia*	*Cunninghamia* spp.	*Cunninghamia lanceolata*
Class IV	No.1, No.16, No.17	Fagaceae	*Quercus*	sect. *Cerris*	*Q. chenii*
Class V	No.10, No.14, No.18	Ulmaceae	*Ulmus*	sect. *Madocarpus*	U. *macrocarpa*, *U. pumila*

3.1 Class I Wood: Larix sect. Multiseriales

3.1.1 Key Anatomical Characteristics

Key anatomical characteristics of this wood class (Samples No.2, No.4, No.5, No.6, No.7, No.9, No.11, No.13) are presented in Figs. 2:

Growth rings

boundaries slightly distinct (Figs. 2a); gradual transition from earlywood to latewood (Figs. 2a).

Tracheids

earlywood tracheids with thin walls (square, rectangular, or polygonal); latewood tracheids with thick walls (rectangular or square) (Figs. 2a, b); tracheid pitting in radial walls (in earlywood only) predominatly uniseriate; helical thickenings in longitudinal tracheids absent (Figs. 2c).

Axial parenchyma

absent (Figs. 2a, b).

Ray type and composition

two types—uniseriate (5–15 cells in height) and fusiform (2–3 cells in width, 3–12 cells in height) (Figs. 2e, f); ray cells are isodiametric or slightly isodiametric, comprising ray tracheids (located at the upper or lower ends of ray parenchyma cells; low rays may consist entirely of ray tracheids) and ray parenchyma cells; inner cell walls of ray tracheids smooth with wavy outer edges, horizontal walls thick with numerous pittings and end walls distinct nodular thickenings (Figs. 2c, d); End walls of ray parenchyma cells distinctly pitted and horizontal walls distinctly pitted (Figs. 2c, d)

Cross-field pitting

Cross-field pitting between ray parenchyma cells and earlywood tracheids Taxodioid-type (2–4 pittings), which is a diagnostic characteristic of *Larix* sect. *Multiseriales* (Pinaceae) (Figs. 2c, d).

Intercellular canals

both of axial intercellular canals (solitary, pore-like, concentrated in latewood and adjacent earlywood zones, numerous, with thick-walled epithelial cells) (Figs. 2a, b) and radial intercellular canals (located within fusiform rays, smaller than axial canals) (Figs. 2e, f) present —a key characteristic of Pinaceae genera such as *Pinus*, *Picea*, *Larix*, *Pseudotsuga*, and *Cathaya*.

3.1.2 Species Identification and Timber Application

The genus *Larix* (Pinaceae) is classified into two sections: *Multiseriales* and *Pauciseriales*. Sect. *Multiseriales* is characterized by isodiametric or slightly isodiametric ray cells and Taxodioid - type Cross-field pitting, whereas sect. *Pauciseriales* exhibits elliptical or long elliptical ray cells and Piceoid - type Cross-field pitting [4, 8]. Microscopic observations and comparative analyses confirmed that Class I wood corresponds to Larix sect. Multiseriales.

Wood of *Larix* sect. *Multiseriales* (e.g., *L. chinensis*, *L. mastersiana*, *L. potaninii*) is lighter, softer, with a uniform structure, less susceptible to cracking, and more decay-resistant compared to that of sect. *Pauciseriales* [8] — rendering it well-suited for secondary load-bearing components (purlins, rafters) that demand balanced mechanical performance, durability, and lightweight properties to reduce the upper structural load. These species are naturally distributed in the Qinling Mountains and Sichuan Province [9]. Nanyang’s geographical proximity to the Qinling Mountains facilitated short-distance land transportation of this timber during the late Qing Dynasty and the Republic of China, reflecting the “near-source material utilization” principle.

3.2 Class II Wood: Pinus subg. Haploxylon, sect. Cembra

3.2.1 Key Anatomical Characteristics

Key anatomical characteristics of this wood class (Samples No.3, No.15) are presented in Figs. 3:

Growth rings

boundaries slightly distinct (Figs. 3a); gradual transition from earlywood to latewood (Figs. 3a).

Tracheids

earlywood tracheids with thin walls (square, rectangular, or polygonal); latewood tracheids with thick walls (rectangular or square) (Figs. 3a, b); tracheid pitting in radial walls (in earlywood only) predominatly uniseriate; helical thickenings in longitudinal tracheids absent (Figs. 3c, d).

Axial parenchyma

absent (Figs. 3a, b).

Ray type and composition

two types—uniseriate (5–15 cells in height) and fusiform (2–3 cells in width, 3–12 cells in height) (Figs. 3e, f); ray cells comprising ray tracheids (located at the upper or lower ends of ray parenchyma cells; low rays may consist entirely of ray tracheids) and ray parenchyma cells; inner cell walls of ray tracheids micro-dentate with wavy outer edges, horizontal walls thick with numerous pittings and end walls non - nodular thickenings (Figs. 3c, d); End walls of ray parenchyma cells smooth (unpitted) pitted and horizontal walls distinctly pitted (Figs. 3c, d)

Cross-field pitting

Cross-field pitting between ray parenchyma cells and earlywood tracheids Window-like-type (1–2 pittings) —a diagnostic characteristic of *Pinus* (Pinaceae) (Figs. 3c, d).

Intercellular canals

both of axial intercellular canals (solitary, pore-like, concentrated in latewood and adjacent earlywood zones, numerous, with thick-walled epithelial cells) (Figs. 3a) and radial intercellular canals (located within fusiform rays, smaller than axial canals) (Figs. 3e, f) present —a key characteristic of Pinaceae genera such as *Pinus*, *Picea*, *Larix*, *Pseudotsuga*, and *Cathaya*.

3.2.2 Species Identification and Timber Application

Pinus (Pinaceae) is classified into two subgenera: *Haploxylon* and *Diploxylon*. Within subg. *Haploxylon*, sect. *Cembra* is characterized by window-like Cross-field pitting, while sect. *Parrya* exhibits Pinoid-type pittings [4–5, 8]. Microscopic analyses confirmed that Class II wood belongs to *Pinus* subg. *Haploxylon*, sect. *Cembra*.

Wood of *Pinus* sect. *Cembra* (e.g., *P. armandii*, *P. koraiensis*) is light, soft, delicate, easy to process, and moderately decay-resistant but low in strength [8]—ideal for non-load-bearing/decorative components (door/window frames, mullions) that require fine carving and do not require high mechanical strength. *Pinus armandii* is distributed in southwestern Henan, Songshan Mountain, Zhongtiao Mountain (southern Shanxi), and the Qinling Mountains (southern Shaanxi) [8–9, 10], aligning with the "local material utilization" principle.

3.3 Class III Wood: Cunninghamia lanceolata

3.3.1 Key Anatomical Characteristics

Key anatomical characteristics of this wood class (Samples No.8, No.12) are presented in Figs. 4:

Growth rings

boundaries distinct (Figs. 4a); gradual transition from earlywood to latewood (Figs. 4a).

Tracheids

earlywood tracheids with thin walls (square, rectangular, or polygonal); latewood tracheids with thick walls (rectangular or square) (Figs. 4a, b); tracheid pitting in radial walls (in earlywood only) predominatly uniseriate; helical thickenings in longitudinal tracheids absent (Figs. 4c, d).

Axial parenchyma

abundant (diffuse and tangential banded) — a typical characteristic of Taxodiaceae (Figs. 4a, b).

Ray type and composition

Uniseriate (rarely biseriate, 5–10 cells in height) (Figs. 4e, f); only ray parenchyma cells (no ray tracheids, distinguishing it from Pinaceae), end walls smooth (unpitted) and horizontal walls distinctly pitted (Figs. 4c, d)

Cross-field pitting

Cross-field pitting between ray parenchyma cells and earlywood tracheids Taxodioid-type (2–4 pittings) — a diagnostic characteristic of Cunninghamia (Figs. 4c, d).

Intercellular canals

absent (Figs. 4a, b, e, f).

Insect infestation

Obvious insect holes in transverse sections (Figs. 4a), indicating weak insect resistance.

3.3.2 Species Identification and Timber Application

Class III wood is characterized by abundant axial parenchyma, no resin canals, rays composed solely of ray parenchyma cells, and Taxodioid-type Cross-field pitting—consistent with *Cunninghamia lanceolata* [4, 8; 11].

Although *Cunninghamia lanceolata* is a dominant species in southern China, Nanyang's location at the north-south climate transition (southern foot of the Funiu Mountains) supports its large-scale distribution in Tongbai, Xixia, and Nanzhao counties [8–9, 10], enabling "local material utilization". The wood's light weight, low shrinkage, and natural decay resistance (attributed to aromatic compounds) [8] make it suitable for rafters—requiring lightweight properties to reduce structural load and decay resistance to extend service life. However, sapwood is susceptible to insect infestation [8], as evidenced by insect holes in Figs. 4a—consistent with the "severe eave rafter infestation" observed in the Introduction. This finding provides a species-specific basis for targeted sapwood preservation in subsequent restoration.

3.4 Class IV Wood: Quercus subg. Lepidabalanus, sect. Cerris

3.4.1 Key Anatomical Characteristics

Key anatomical characteristics of this wood class (Samples No.1, No.16, No.17: columns, beams) are presented in Figs. 5:

Growth rings

Growth ring boundaries distinct (Figs. 5a).

Vessels

Wood ring-porous, earlywood vessels 1–3 cells wide (round, oval, or elliptical), tyloses and deposits in vessels common, and latewood vessels irregular polygonal (Figs. 5a); latewood vessels in radial pattern (Figs. 5a, b); latewood vessels exclusively solitary (90% or more) and occasionally short radial multiples (2 vessels) (Figs. 5b); simple perforation plates; intervessel pitting alternate; helical thickenings in vessel elements absent (Figs. 5e).

Vasicentric tracheids

present, surrounding earlywood vessels (Figs. 5c).

Axial parenchyma

apotracheal axial parenchyma diffuse and diffuse-in-aggregates, axial parenchyma in narrow bands or lines up to three cells wide, rhomboidal crystals present (Figs. 5a, b, c, d).

Ground tissue fibres

fibres very thick-walled with distinctly bordered pittings (Figs. 5c, d).

Ray type and composition

rays of two distinct sizes —narrow (uniseriate) and wide (larger rays commonly > 10-seriate, ray cells are extremely tall, often exceeding the limits of the section) (Figs. 5a, b, e, f) — a diagnostic characteristic of *Quercus* (Fagaceae); all ray cells procumbent (Figs. 5c, d, e, f).

Intercellular canals

Absent (Figs. 5a, b, e, f).

3.4.2 Species Identification and Timber Application

Quercus (Fagaceae) is classified into two subgenera: *Erythrobalanus* and *Lepidabalanus*. Within subg. *Lepidabalanus*, sect. *Cerris* is characterized by round/oval latewood vessels (few, thick-walled), minimal tyloses in earlywood vessels of heartwood, and wide, low, fusiform Ray composition; sect. *Prinus* exhibits irregular polygonal latewood vessels (numerous, thin-walled), abundant tyloses, and narrow, high, linear rays; sects. *Ilex* and *Suber* are diffuse-porous [8]. Microscopic comparisons confirmed that Class IV wood belongs to *Quercus* subg. *Lepidabalanus*, sect. *Cerris* [5, 8, 12–16].

Wood of *Quercus* sect. *Cerris* (e.g., *Q. variabilis*, *Q. acutissima*, *Q. chenii*) has an air-dry density of 0.93 g/cm³, extremely high hardness and strength, and strong decay resistance [8]—ideal for core load-bearing components (columns) that support the building's vertical load. However, it is susceptible to infestation by Anoplophora glabripennis and Lyctus brunneus [8]. *Quercus chenii* is widely distributed in Nanyang and southwestern Henan [8–9, 17], conforming to the "local material utilization" principle. Column base decay observed in field investigations is attributed to long-term moisture exposure (ground contact) rather than insufficient decay resistance — highlighting the need for moisture-proof treatment in restoration.

3.5 Class V Wood: Ulmus sect. Madocarpus

3.5.1 Key Anatomical Characteristics

Key anatomical characteristics of this wood class (Samples No.10, No.14, No.18: columns, beams) are presented in Figs. 6:

Growth rings

Growth ring boundaries distinct (Figs. 6a).

Vessels

Wood ring-porous, earlywood vessels 1–3 cells wide (round, oval, or elliptical), tyloses and deposits in vessels common, and latewood vessels irregular polygonal (Figs. 6a); latewood vessels in tangential bands (Figs. 6b); latewood vessels clusters common and occasionally short radial multiples (2 vessels) (Figs. 6b); simple perforation plates (Figs. 6c); intervessel pitting alternate (Figs. 6c); helical thickenings only in narrower vessel elements — a diagnostic characteristic of *Ulmus* (Ulmaceae) (Figs. 6c, d).

Vasicentric tracheids

absent.

Axial parenchyma: Axial parenchyma: Abundant, mainly paratracheal axial parenchyma: axial parenchyma vasicentric in earlywood zone, and axial parenchyma bands more than three cells wide in latewood zone (Figs. 6a, b).

Ground tissue fibres

fibres very thick-walled with distinctly bordered pittings (Figs. 6c, d).

Ray type and composition

larger rays commonly 4- to 10-seriate (Figs. 6a, b, e, f); all ray cells procumbent (Figs. 6c, d, e, f).

Intercellular canals

Absent (Figs. 6a, b, e, f).

Insect damage features

the transverse-section shows distinct insect holes (Figs. 6a), indicating weak insect resistance.

3.5.2 Species Identification and Timber Application

The genus *Ulmus* (Ulmaceae) is classified into two sections: *Madocarpus* and *Microptelea*. sect. *Madocarpus* (air-dry density ~ 0.65 g/cm³) is lighter than sect. *Microptelea* (~ 0.90 g/cm³) and is distinguished by its ring-porous vessels, well-developed spiral thickenings on latewood vessel walls, and multiseriate non-storied rays. Microscopic comparative analysis confirmed that Class V wood belongs to *Ulmus* sect. *Madocarpus* [5, 8, 11–12, 13–14, 18–20].

Wood of *Ulmus* sect. *Madocarpus* (e.g., *U. macrocarpa*, *U. pumila*) exhibits high hardness, excellent wear resistance, superior tangential compressive and bending strength, and aesthetically pleasing grain patterns [8]—making it a preferred choice for core load-bearing components (columns, beams) responsible for transmitting vertical and horizontal structural loads. *Ulmus macrocarpa* is widely distributed in southwestern Henan, while *U. pumila* is extensively cultivated as a local species in Nanyang [8–9, 16], fully aligning with the “local material utilization” principle. However, consistent with prior research [8], this wood class exhibits weak insect resistance, as evidenced by the distinct insect holes observed in transverse sections (Figs. 6a). This finding underscores the necessity of targeted insect-proof treatments (e.g., injection of environment-friendly insecticides) during the restoration process to mitigate further biological deterioration.

3.6 Timber Selection Principles of Wooden Components in Sunjialou

Based on the comprehensive identification results, the timber selection for the wooden components of the Sunjialou Cultural Relic Building exhibits dual core characteristics of "functional adaptation" and "regional resource dependence", which collectively reflect the profound construction wisdom of Nanyang craftsmen during the late Qing Dynasty and the Republic of China.

3.6.1 Functional Adaptation: Precise Matching of Wood Properties and Component Functions

A highly significant correlation was observed between the intrinsic properties of selected timbers and the functional requirements of building components, embodying the traditional construction philosophy of "selecting materials based on their properties":

Core load-bearing components (columns, beams): high-strength, decay-resistant hardwoods (*Quercus* sect. *Cerris*, *Ulmus* sect. *Madocarpus*) were strategically employed. Specifically, *Ulmus* sect. *Madocarpus* exhibits an air-dry density of ~ 0.65 g/cm³, a bending strength of 80–90 MPa, and a tangential compressive strength of 32–40 MPa; in contrast, *Quercus* sect. *Cerris* possesses a higher air-dry density (~ 0.90 g/cm³), a bending strength of 97–140 MPa, and a tangential compressive strength of 44–61 MPa [8]. These mechanical properties fully meet the stringent load-bearing requirements of core structural elements, ensuring the long-term structural stability.

Secondary load-bearing components (purlins, rafters): decay-resistant, lightweight softwoods with straight grains (*Larix* sect. *Multiseriales*, *Cunninghamia lanceolata*) were selected. Their lightweight nature effectively reduces the overall structural load imposed on the core system, while their inherent decay resistance inhibits fungal colonization and decomposition, thereby extending the service life of these components.

Non-load-bearing/decorative components (doors, windows): easily workable, fine-textured softwoods (*Pinus* sect. *Cembra*, specifically *P. armandii*) were prioritized. The light and soft texture of Pinus armandii facilitates intricate carving and processing, enabling the realization of elaborate decorative patterns that align with local folk aesthetic preferences.

3.6.2 Regional Resource Dependence: Embodiment of "Local or Near-Source Material Utilization"

The timber selection strictly adheres to the time-honored principle of “local or near-source material utilization”, which is closely linked to the regional resource endowments and transportation conditions of the era:

Local material utilization: *Pinus* sect. *Cembra* (*P. armandii*), *Cunninghamia lanceolata*, *Ulmus* sect. *Madocarpus* (*U. macrocarpa*), and *Quercus* sect. *Cerris* (*Q. chenii*) are either native species or widely cultivated in Nanyang and southwestern Henan. The adoption of local timbers eliminated the need for long-distance transportation, significantly reducing construction costs and minimizing material during transit.

Near-source material utilization: *Larix* sect. *Multiseriales* is naturally distributed in the Qinling Mountains, which are geographically adjacent to Nanyang. During the late Qing Dynasty and the Republic of China, this timber could be transported via short-distance overland routes, making it a practical near-source alternative when local softwood supplies were insufficient for secondary load-bearing components.

This characteristic not only reflects the dependence of Nanyang’s modern construction supply chain on local forest resources (e.g., Funiu Mountains, Tongbai Mountains) but also confirms the constraining influence of transportation capacity on timber selection in ancient construction practices. Collectively, these findings provide critical tangible evidence for reconstructing the regional construction techniques and resource utilization patterns of modern-era architecture in southwestern Henan.

4. Conclusions

This study systematically identified the timber species of wooden components in the Sunjialou Cultural Relic Building through microscopic anatomical observation and taxonomic comparison, clarifying the species composition, underlying timber selection principles, and practical implications for conservation and restoration. The key conclusions are as follows:

(1) Timber species composition. A total of 18 samples collected from columns, beams, purlins, rafters, and doors/windows were identified as 5 taxonomic groups belonging to 4 families: *Larix* sect. *Multiseriales* (Pinaceae), *Pinus* sect. *Cembra* (Pinaceae), *Cunninghamia lanceolata* (Taxodiaceae), *Quercus* sect. *Cerris* (Fagaceae), and *Ulmus* sect. *Madocarpus* (Ulmaceae). This research systematically establishes the timber species pedigree of the building’s wooden components, filling the gap in current knowledge of the material composition for this heritage site

(2) Dual core selection principles. The timber selection for the Sunjialou Cultural Relic Building is characterized by distinct “functional adaptation” and “regional resource dependence”. Functional adaptation: Core load-bearing components utilize high-strength, decay-resistant hardwoods; secondary load-bearing components employ decay-resistant, lightweight softwoods; and non-load-bearing/decorative components adopt easily workable, fine-textured softwoods. This pattern achieves precise matching between wood properties and component functions, reflecting the rational construction logic of traditional craftsmen. Regional resource dependence: Except for *Larix* sect.

Multiseriales (sourced from the adjacent Qinling Mountains), the other four taxonomic groups are local species in Nanyang or southwestern Henan. This confirms the adherence to the "local or near-source material utilization" tradition during the late Qing Dynasty and the Republic of China, embodying efficient resource utilization strategies and the practical wisdom of regional craftsmen.

(3) Guidelines for restoration and replacement: The identification results clarify the original timber species for each functional component (columns/beams: *Ulmus* sect. *Madocarpus*, *Quercus* sect. *Cerris*; purlins/rafters: *Larix* sect. *Multiseriales*, *Cunninghamia lanceolata*; doors/windows: *Pinus* sect. *Cembra*), providing a robust scientific foundation for adhering to the principles of "minimum intervention" and "authenticity protection" in restoration work. To avoid restoration failure caused by inappropriate species selection, the following recommendations are proposed in accordance with Article 7.2.1 of "*Technical Standard for Maintenance and Strengthening of Ancient Timber Structures*"(GB/T 50165—2020) [20]:

Priority to original species: For columns and beams, prioritize the use of *Quercus* sect. *Cerris* (*Q. chenii*) and *Ulmus* sect. *Madocarpus* (*U. macrocarpa*), supplemented by targeted insect-proof and moisture-proof treatments; for purlins and rafters, select *Larix* sect. *Multiseriales* and *Cunninghamia lanceolata*, with emphasis on sapwood preservation (e.g., traditional tung oil coating, application of modern environment-friendly preservatives); for doors and windows, prioritize Pinus armandii to ensure consistency in processing performance and decorative effects.

Scientific selection of alternative species: In cases where original species (e.g., high-quality large-diameter *Larix* sect. *Multiseriales*, *Quercus* sect. *Cerris*) are scarce, alternative species should be selected in accordance with Tables 7.2.1-1 and 7.2.1-2 of "*Technical Standard for Maintenance and Strengthening of Ancient Timber Structures*" (GB/T 50165—2020)[20]. The selected alternatives must have strength grades not lower than those of the original components, and priority should be given to species within the same genus with equivalent mechanical properties (e.g., substitute species for *Quercus* sect. *Cerris* should be selected from the *Quercus* genus with comparable density and strength).

In summary, this study provides a scientific basis for the precise restoration of wooden components in the Sunjialou Cultural Relic Building and serves as a representative case study for constructing timber species databases, restoring regional construction techniques, and investigating resource utilization patterns of modern-era ancient architecture in southwestern Henan. It holds significant reference value for the conservation and restoration of similar ancient wooden structures across China.

Declarations

Authors' contributions

QXH: writing-original draft preparation; ZWT: writing-original draft preparation; FMX: writing-original draft preparation; LXH: experiment operation; XTY: experimental operation; LZY: experimental operation; JHD:

data interpretation; LB: data interpretation; YY: reviewing and editing. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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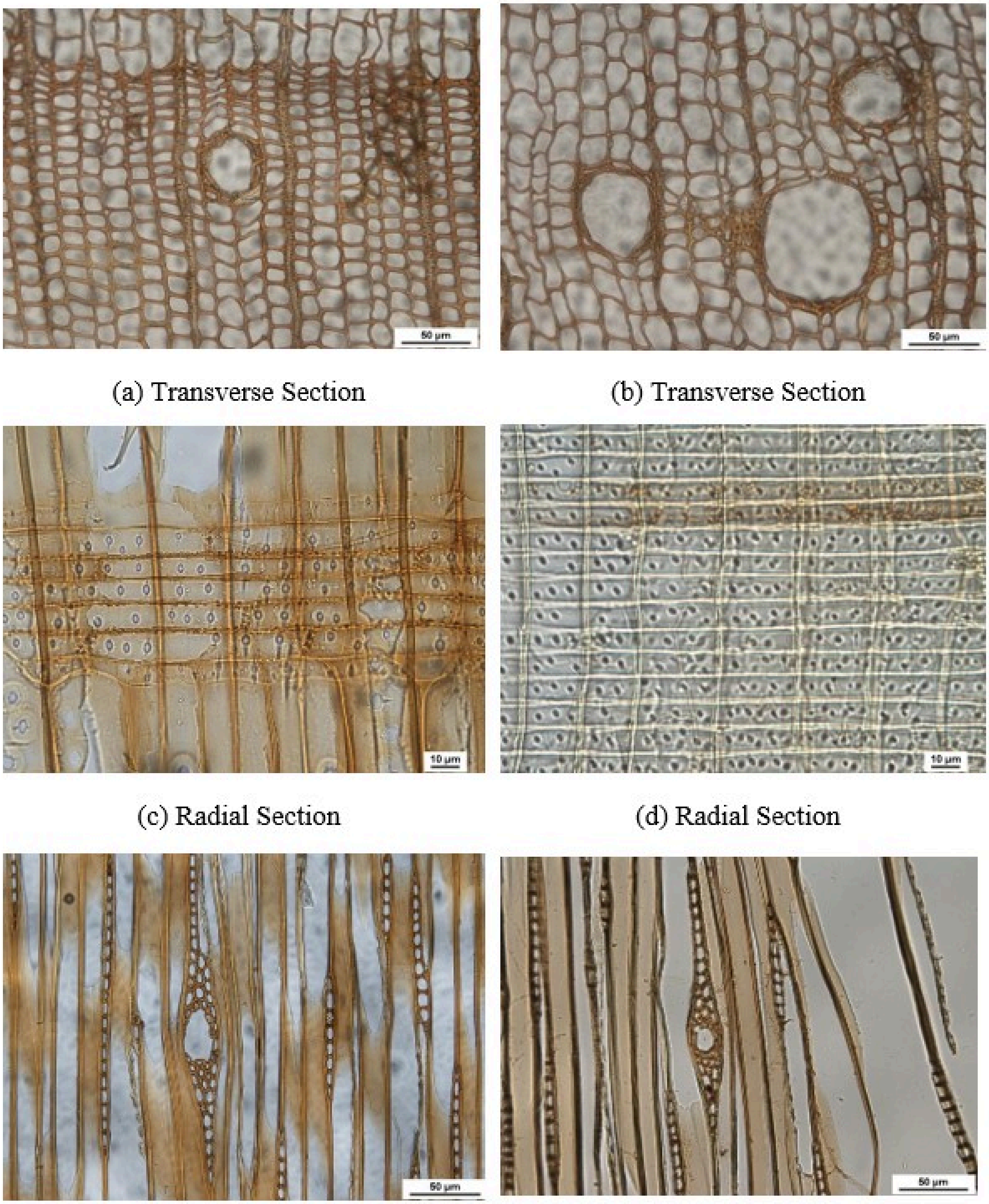
Figures

(a) Decay of eave purlins and rafters
(b) Decay of eave purlins and rafters
(c) Insect infestation of eave purlins
(d) Insect infestation of eave rafters
(e) Decay of column bases
(f) Decay of column bases

Figure 1

Current preservation status of the Sunjialou Cultural Relic Building in Nanyang City



(a) Transverse Section (b) Transverse Section

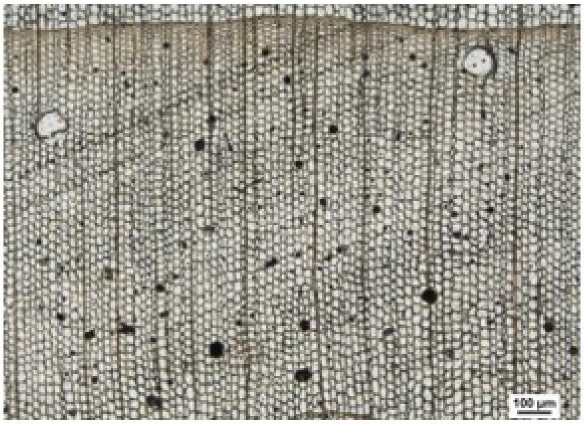
(c) Radial Section (d) Radial Section

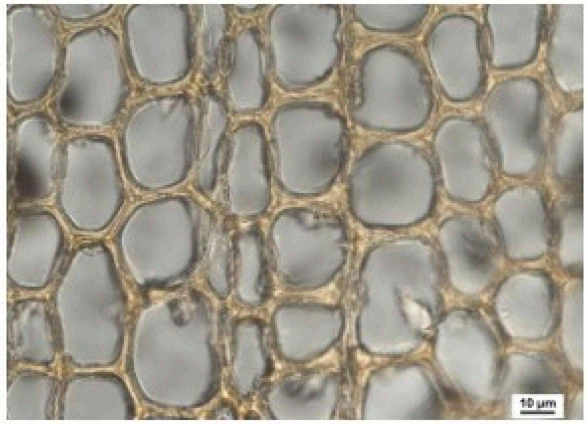
(e) Tangential Section (f) Tangential Section

Figure 2

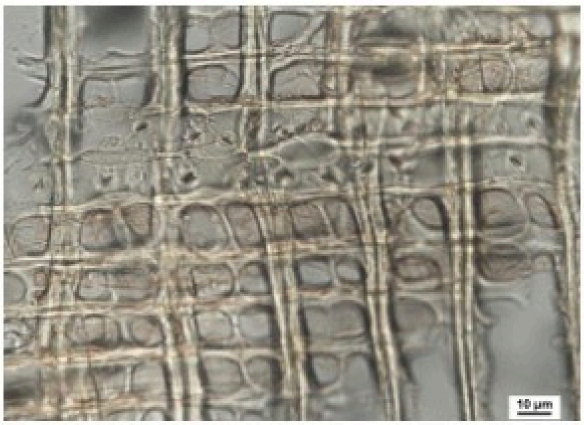
Identification result: *Larix* sect. *Multiseriales*

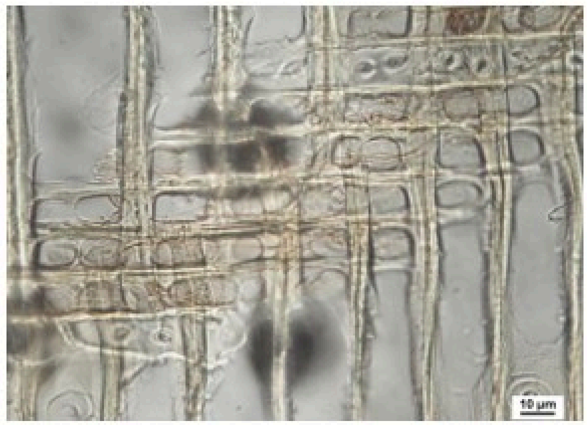
Anatomical structure of Class I wood



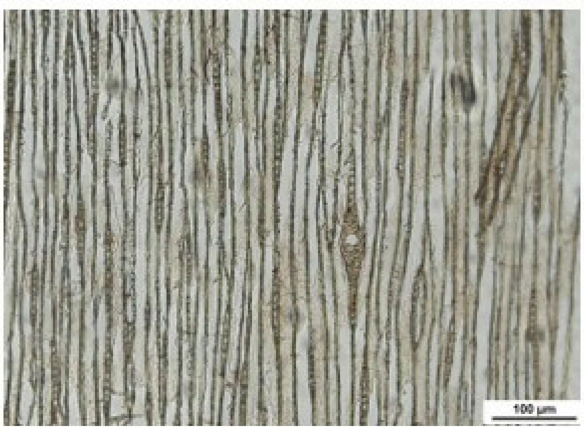


(a)Transverse Section (b)Transverse Section





(c)Radial Section (d)Radial Section

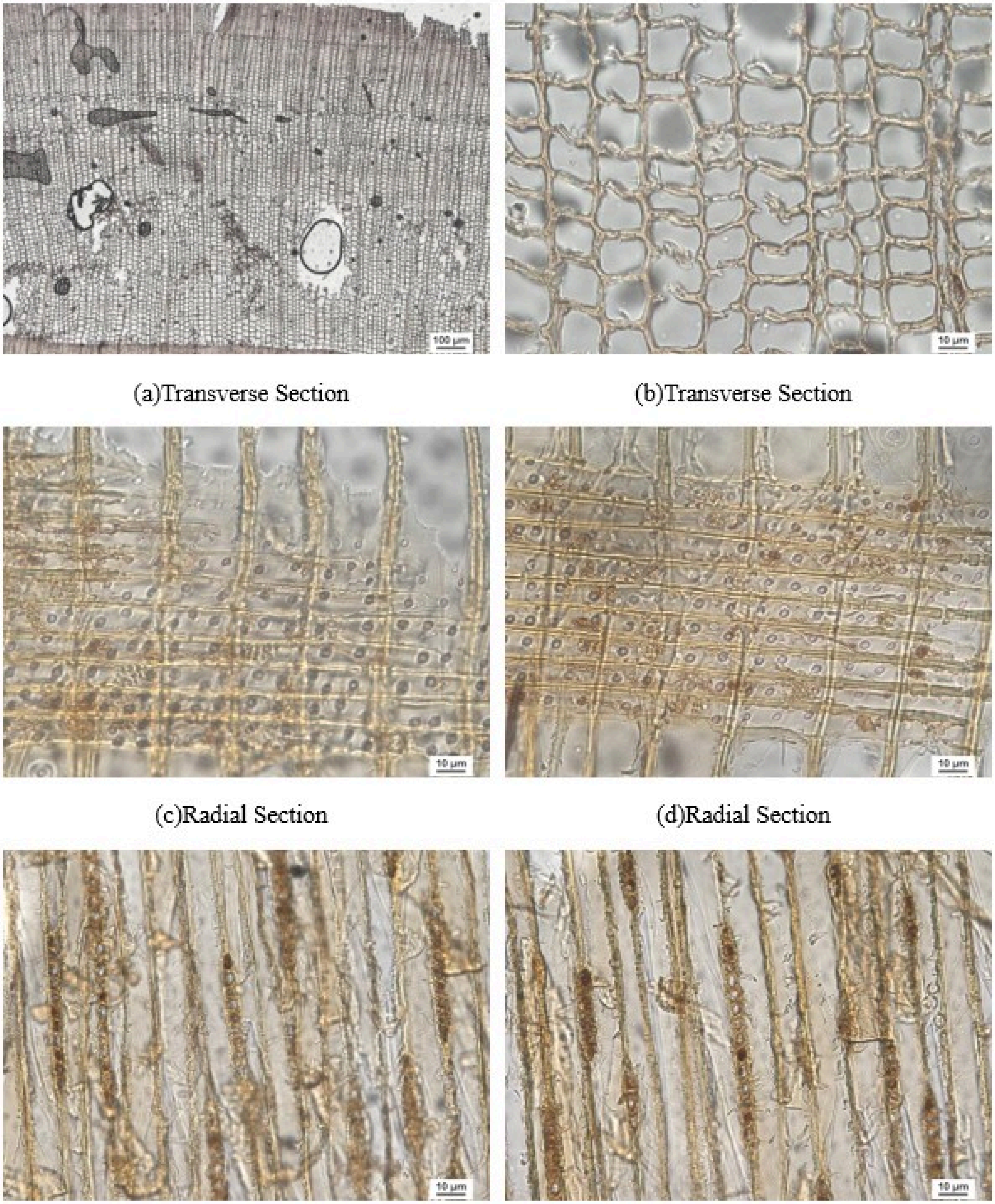


(e)Tangential Section (f)Tangential Section

Figure 3

Identification result: *Pinus* sect. *Cembra*

Anatomical structure of Class II wood



(a)Transverse Section (b)Transverse Section

(c)Radial Section (d)Radial Section

(e)Tangential Section (f)Tangential Section

Figure 4

Identification result: *Cunninghamia lanceolata*

Anatomical structure of Class III wood

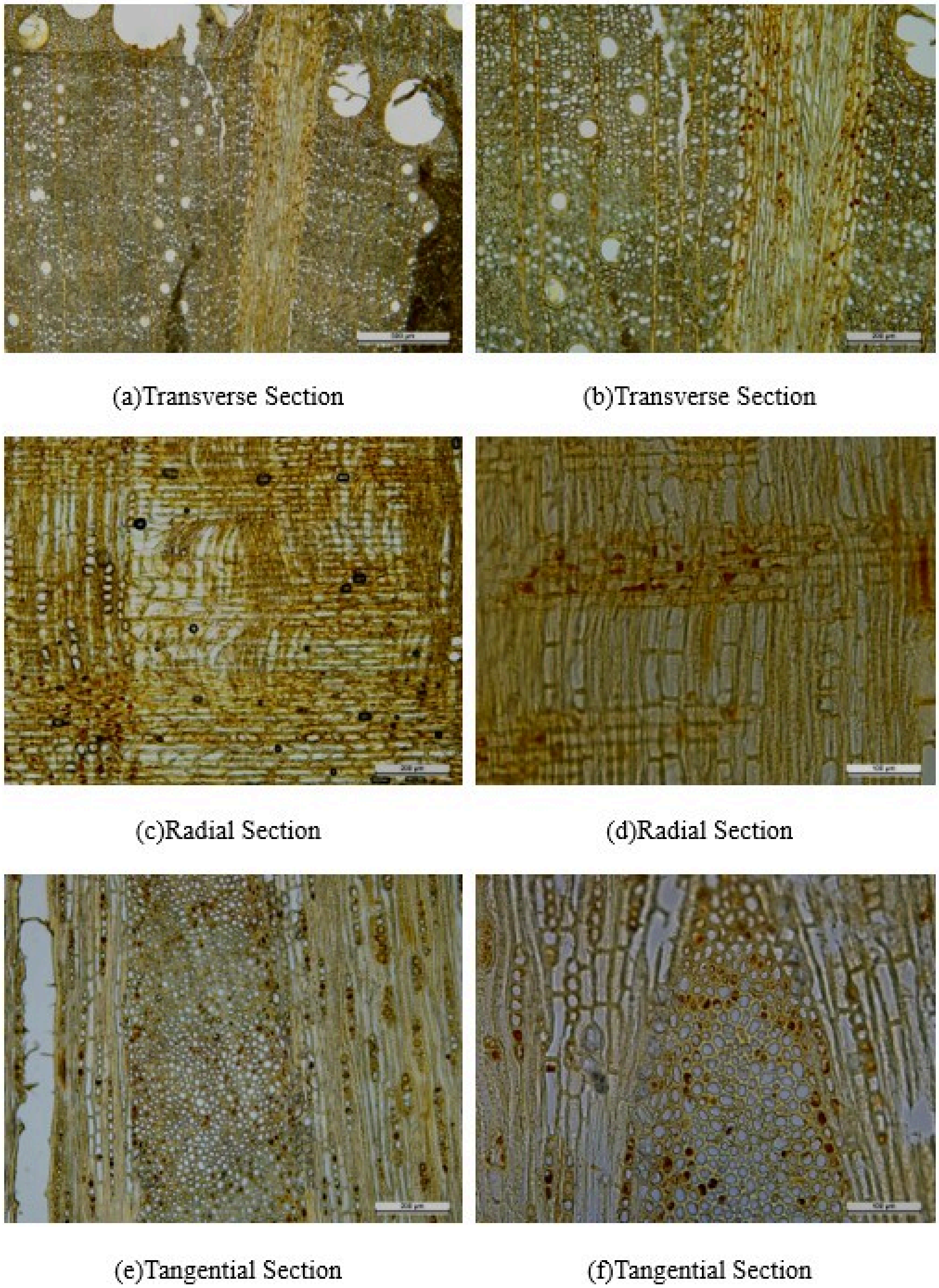


Figure 5

Identification result: *Quercus* sect. *Cerris*

Anatomical structure of Class IV wood

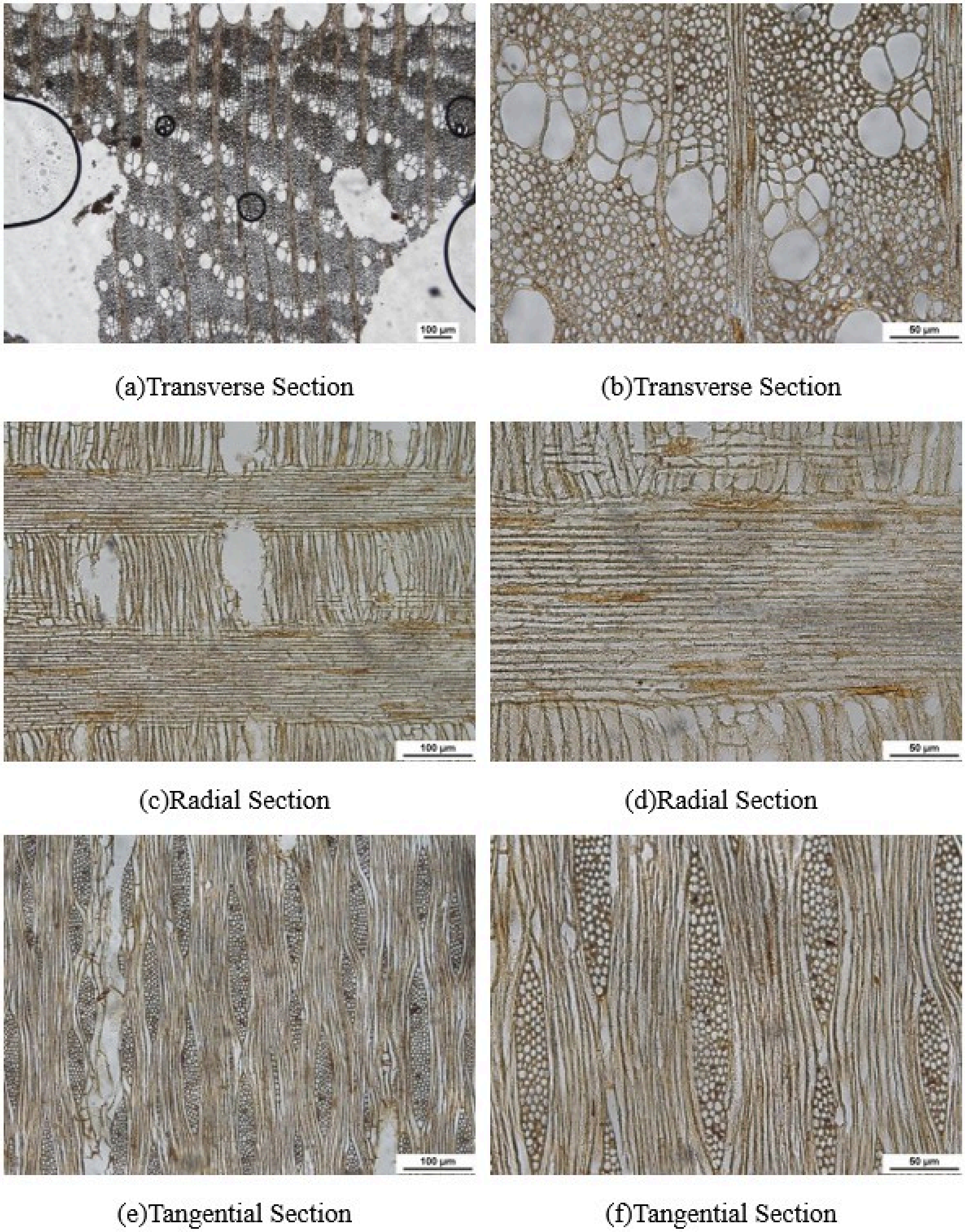


Figure 6

Identification result: *Ulmus* sect. *Madocarpus*

Anatomical structure of Class V wood