

Performance of *Cunninghamia lanceolata* / *Uncaria* Composite Particleboard: Part 2

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Thinned Chinese fir (*Cunninghamia lanceolata*) and waste stems of *Uncaria* were used as raw wood materials with melamine–urea–formaldehyde as a co-condensation resin adhesive to produce particleboard. The effects of *Uncaria* stem incorporation on the composite's nail-holding capacity, antibacterial activity, decay resistance, insect resistance, and fire retardancy were investigated. GC-MS analysis identified 19 bioactive compounds in *Uncaria* stems, including esters, terpenes, carboxylic acids, and indole alkaloids. At 50% *Uncaria* stem mass fraction, nail-holding strength peaked at 170.8 N/mm, a 10.3% increase over pure fir boards. Anti-mold, decay, termite resistance, and fire-retardancy tests demonstrated that *Uncaria*'s active components significantly mitigated fir's inherent vulnerabilities via a dual "chemical inhibition + physical barrier" mechanism. A 50% substitution reduced mold coverage from 100% to 3%, while 75% substitution decreased white-rot fungal mass loss from 35.8% to 25.7% and linearly lowered termite-induced mass loss from 18.2% to 7.5%. Cone calorimetry revealed that 75% *Uncaria*-substituted composites exhibited a 4.6% reduction in peak heat release rate, a 4-second ignition delay, and increased char residue from <5% to 11%, achieving GB/T 8624 Class B1 fire-retardant rating. *Uncaria* waste stems thus serve as a functional filler for fir particleboard, endowing it with multi-bio-durability and flame-retardant properties. This offers theoretical and technical support for the high-value utilization of agro-forestry waste and development of green wood-based composites.

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INTRODUCTION

With global forest resources becoming increasingly scarce and the “dual-carbon” strategy gaining momentum, upgrading the performance of wood-based materials at a lower environmental cost has become a shared priority for the forest products industry and materials science (Yang *et al.* 2018; Jin 2022; Yan *et al.* 2022; Wang *et al.* 2024). Chinese fir (*Cunninghamia lanceolata*), the dominant plantation species in southern China, is widely used in the production of particleboard, fiberboard, and other wood composites due to its rapid growth and large standing volume (Wang *et al.* 2019; Li *et al.* 2024; Zhong *et al.* 2024). Nevertheless, the inherently high contents of sugars and starch, together with a

high porosity, make Chinese fir products highly susceptible to the combined attack of molds, decay fungi, termites, and fire, which shortens its service life, raises maintenance costs, and severely limits their high-end and functional applications (Cavdar 2014; Bakir *et al.* 2021). Traditional solutions rely on external addition of chemical preservatives, flame retardants, and insecticides; however, these additives often suffer from leaching, toxic residues, and secondary pollution, thereby failing to meet the health and safety requirements of green manufacturing and interior-grade materials (Wu *et al.* 2021; Yu *et al.* 2021). Therefore, developing an endogenous modification strategy that can simultaneously endow wood-based composites with “self-antibacterial, self-preservative, and self-flame-retardant” capabilities has become the key to overcoming current technological bottlenecks.

Agricultural and forestry biomass waste branches constitute an enormous, renewable resource; yet, owing to a lack of high-value utilization pathways, they are commonly burned on-site or simply discarded, leading to resource waste and additional carbon emissions. *Uncaria rhynchophylla* (Miq.) Miq. ex Havil, a major medicinal vine widely cultivated in Guizhou, Yunnan, and adjacent provinces, generates vast quantities of pruning residues annually. Modern phytochemical investigations have shown that *Uncaria* stems are rich in indole alkaloids, terpenes, and other bioactive secondary metabolites. These compounds not only exhibit pronounced antibacterial, insecticidal, antioxidant, and free-radical-scavenging activities, but they also release nitrogen-centered radicals and inert gases during pyrolysis, imparting excellent char-forming and flame-retardant potential (Geng *et al.* 2019; Guo *et al.* 2019; Zhan 2022; Hu 2024). At present, however, *Uncaria* waste branches are mainly used as roughage or low-grade fuel, and their functional value remains largely untapped. Integrating these residues into Chinese-fir-based particleboard could realize a circular-economy strategy of “waste-to-weakness remediation,” while the *in-situ*, sustained release of active components could establish a multi-dimensional protection network combining “chemical inhibition – physical barrier – structural reinforcement,” thereby offering a green, durable, and synergistic paradigm for wood-composite modification. Although previous studies have explored plant-derived active ingredients for wood protection, most have focused on single-function (*e.g.*, decay or fire resistance) macroscopic evaluations, lacking a systematic linkage among “chemical fingerprint – microstructure – macro-performance” (Fu 2015; Fernandez-Costas *et al.* 2017; Wozniak 2022). Moreover, differences among wood species in particle density, surface free energy, pore structure, and heat/mass-transfer characteristics lead to complex couplings in adhesive distribution, interfacial bonding, and hot-pressing behaviour, ultimately influencing the balance of mechanical, durability and combustion properties. Clarifying the multi-scale synergistic mechanisms between fir and *Uncaria* particles and identifying the optimal substitution range are therefore the central scientific issues for industrializing this strategy.

Building on the above, this study employed thinned Chinese fir and *Uncaria* waste-branches as the woody raw materials and a laboratory-synthesized melamine–urea–formaldehyde (MUF) co-condensation resin as the adhesive (Zhang *et al.* 2025). The research systematically investigated how the incorporation level of *Uncaria* branches affected the nail-holding capacity, antibacterial activity, decay resistance, insect resistance, and flame retardancy of the resulting composite particleboards. Gas Chromatography-Mass Spectrometry (GC-MS) was used to decode the chemical fingerprint of *Uncaria* branches, identifying the types and contents of bioactive constituents. Next, combining density-profile mapping with mechanical testing, the structure–performance coupling rules were

elucidated. Finally, multi-scale evaluations including mold, white-rot fungus, termite, and cone-calorimetry tests were conducted to clarify how the active components' function within a three-dimensional protection network spanning the “gas phase – condensed phase – structural phase”. The outcomes are expected to provide theoretical guidance for the high-value utilization of agro-forestry waste, lay a technical foundation for the design and industrialization of green, functional wood-based composites, and offer new insights for a circular economy of “forests nurturing forests, waste upgrading wood”.

EXPERIMENTAL

Materials

Melamine (99 wt%) and urea (99 wt%), analytical grade, were supplied by Sinopharm Chemical Reagent Co., Ltd. Formaldehyde (37 wt%), analytical grade, was purchased from Chengdu Jinshan Chemical Reagent Co., Ltd. All other chemicals, *e.g.*, NaOH and $(\text{NH}_4)_2\text{SO}_4$ used were of analytical grade and obtained from Sinopharm Chemical Reagent Co., Ltd. Chinese fir particles and *Uncaria* particles (moisture content 5%) were provided by the State-Owned Zhazuo Forest Farm, Guizhou Province. Melamine–urea–formaldehyde (MUF) co-condensation resin was synthesized in-house; its viscosity was 103.2 mPa·s and its solid content 55% (Li *et al.* 2023; Zhang *et al.* 2025).

Preparation of the Particleboard

Prior to hot-pressing, 1.5% $(\text{NH}_4)_2\text{SO}_4$ (based on resin solid) was added to the MUF adhesive, stirred uniformly, and allowed to stand for 5 min. Single-layer laboratory particleboards (200 mm × 200 mm × 10 mm) with a target density of 0.70 g/cm³ were produced. The resin was applied by spraying at 10% of the oven-dry particle mass. Maximum hot-pressing pressure was 33 kg/cm², temperature 140 °C, and total pressing time 8 min, following a three-stage profile (2 min – 4 min – 2 min). To evaluate the effect of the fir/*Uncaria* mass ratio on board performance, panels were manufactured at ratios of 100:0, 75:25, 50:50, 25:75, and 0:100.

Nail-holding Performance Test

Following GB/T 14018 (2009), all particleboard specimens were conditioned for six months under constant temperature, humidity, and good ventilation until their moisture content stabilized at approximately 12%. A WDS-50 kN universal testing machine was employed, applying a uniform loading rate of 2.5 mm/min. Each self-tapping screw nail-holding test was completed within 10 to 60 min. After testing, the maximum load was recorded and the load–displacement curve data were saved. The final nail-holding strength was reported as the mean of twenty replicates, and the standard deviation was less than 10%.

Vertical Density Profile Test

A DAX 6000 density profiler (GreCon, Germany) with a measurement accuracy of ±0.5% of full scale and a scanning speed of 0.4 mm/s was employed. Particleboard specimens were cut to 50 mm × 50 mm and the density distribution along the thickness direction was determined for each sample, thereby evaluating how different mass ratios of Chinese fir to *Uncaria* particles influence the board's density profile.

Mold and Decay Resistance Test

For mold resistance, specimens measuring 20 mm × 50 mm × 5 mm were cut from the particleboards and tested according to GB/T 18261 (2013). For decay resistance, specimens measuring 20 mm × 20 mm × 10 mm were prepared and evaluated in accordance with GB/T 13942.1 (2009).

Termite Resistance Test

Specimens measuring 20 mm × 20 mm × 10 mm were cut from the particleboards and evaluated according to the American Wood Protection Association standard AWWA E1-97 (Yu *et al.* 2021).

Fire-Retardancy Test

Combustion performance was assessed using a VOUCH 6810 cone calorimeter (Suzhou Yangyi Worch). Samples were exposed to a radiant heat flux of 50 kW/m², and key parameters including the heat release rate (HRR) were recorded.

GC-MS Analysis

Uncaria branch powder was placed in an Erlenmeyer flask, covered with methanol, and subjected to ultrasonic extraction for 45 min. The extract was filtered to remove residues. Analyses were performed using the extract on an Agilent 7890A-5975C GC-MS system (USA). Chromatographic conditions used: HP-17MS capillary column (30.0 m × 250 µm, 0.25 µm film); initial oven temperature 45 °C held for 4 min, then ramped at 13 °C/min to 280 °C and held for 15 min; injector temperature 250 °C; transfer line 280 °C; carrier gas He at 1.0 mL/min; split ratio 20:1; injection volume 1.0 µL. MS conditions: EI source; electron energy 70 eV; ion-source temperature 230 °C; quadrupole 150 °C; scan mode; mass range 15 to 500 u.

The detected components were qualitatively determined by NIST11, retention time, and retention index of MS database; the column loss peak was deducted from the database. In addition, the components were quantified through the area normalization method, that is, the percentage of the peak area of the identified components in the area sum of all the identified component was taken as the quantification result.

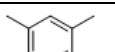
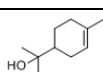
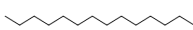
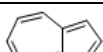
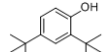
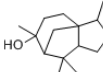
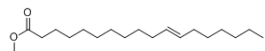
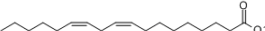
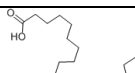
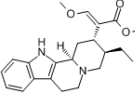
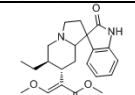
RESULTS AND DISCUSSION

GC-MS Analysis

The *Uncaria* extract is chemically complex, with alkaloids generally regarded as the principal bioactive constituents (Geng *et al.* 2019; Guo *et al.* 2019; Zhan 2022; Hu 2024). To further clarify its composition, the extract was analyzed by GC-MS; the total ion chromatogram is shown in Fig. 1, and the identified compounds are listed in Table 1. Table 1 and Fig. 1 reveal that esters were the most abundant class, followed sequentially by terpenes, carboxylic acids, and alkaloids, together with minor amounts of aldehydes and azulene derivatives.

Most constituents contained polar functional groups centered on N or O, and the molecules were rich in reactive moieties such as hydroxyl, carbonyl, aldehyde, imine, and heterocyclic rings. These structural features imply that *Uncaria* branches have inherent antibacterial, antifungal, insecticidal, and flame-retardant capabilities. Consequently, particleboards fabricated by combining *Uncaria* with Chinese fir are expected to inherit these multi-functional properties.

Table 1. The Main Peaks of GC-MS and their Assignment

No .	RT (min)	Compound	Molecular Formula	Chemical Structure
1	11.31	Nonanal	C ₉ H ₁₈ O	
2	11.78	Benzene, 1,2,4,5-tetramethyl-	C ₁₀ H ₁₄	
3	12.46	Benzene, 1,2,3,4-tetramethyl-	C ₁₀ H ₁₄	
4	12.84	Benzene, 1-ethyl-2,4-dimethyl-	C ₁₀ H ₁₄	
5	13.83	<i>alpha</i> -Terpineol	C ₁₀ H ₁₈ O	
6	14.53	Tetradecane	C ₁₄ H ₃₀	
7	14.63	Naphthalene	C ₁₀ H ₈	
8	14.80	Azulene	C ₁₀ H ₈	
9	16.27	Longifolene	C ₁₅ H ₂₄	
10	16.37	Caryophyllene	C ₁₅ H ₂₄	
11	16.52	1H-3a,7-Methanoazulene, octahyd	C ₁₅ H ₂₄	
12	18.25	2,4-Di-tert-butylphenol	C ₁₄ H ₂₂ O	
13	19.68	Cedrol	C ₁₅ H ₂₆ O	
14	22.45	Palmitic acid	C ₁₆ H ₃₂ O ₂	
15	23.71	11-Octadecenoic acid, methyl ester	C ₁₉ H ₃₆ O ₂	
16	23.88	9,12-Octadecadienoic acid (Z,Z)-, methyl ester	C ₁₉ H ₃₄ O ₂	
17	24.38	<i>trans</i> -13-Octadecenoic acid	C ₁₈ H ₃₄ O ₂	
18	29.95	Hirsutine	C ₂₂ H ₂₈ N ₂ O ₃	
19	26.88	Rhynchophylline	C ₂₂ H ₂₈ N ₂ O ₄	

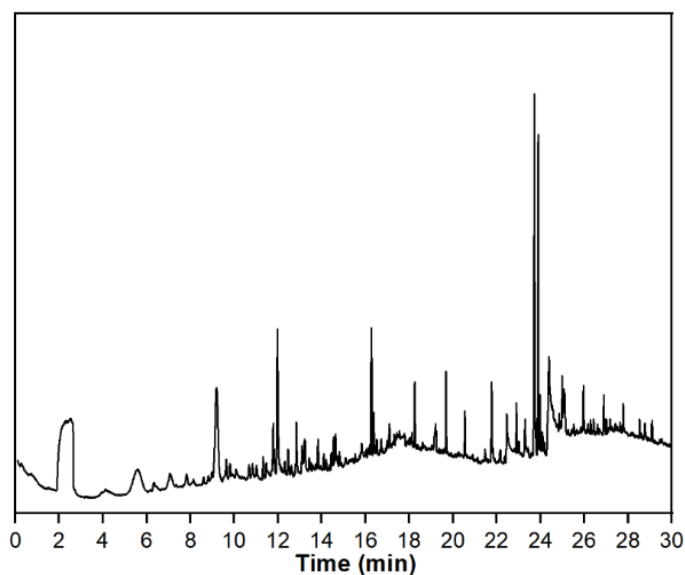


Fig. 1. GC-MS curves of the branches of *Uncaria*

Vertical Density Profile (VDP) Analysis

The vertical density profile (VDP) is a key structural characteristic of particleboard and one of the primary factors influencing its physical–mechanical performance. Under a constant average board density, an increase in surface-layer density is accompanied by a decrease in core-layer density yields a steeper VDP curve (Xi *et al.* 2019; Zhang *et al.* 2025).

As shown in Fig. 2, all boards exhibited a similar through-thickness VDP pattern: high surface density and low core density. The density maximum did not coincide with the outermost surface but was located 0.5 mm beneath it. From this peak, density dropped sharply toward the faces—reaching the board’s absolute minimum at the very surface—while it declined gradually toward the core, where another minimum was observed. Overall, the density gradient from surface to core followed a “low–high–low–high–low” sequence. Moreover, the VDP curves were not smooth, indicating density variation within the cross-section. This pattern arises because, at the onset of hot-pressing, the outermost veneer directly contacts the heated platens. Consequently, the MUF adhesive at the extreme surface cures prematurely before significant compression occurs; thereafter, the applied pressure has little effect on the already solidified layer, yielding very low surface density. In contrast, the entire surface stratum later experiences both elevated temperature and high pressure, resulting in pronounced densification (Zhang *et al.* 2022, 2025). Meanwhile, the core remains cooler and less compressed, hence its lower density. Moreover, all VDP curves exhibited asymmetric “saddle-shaped” profiles, with unequal peak densities at the top and bottom faces. This asymmetry is inevitable because the bottom face is heated first, giving those fibers greater plasticity when the press closes, and heat transfer initiates from this side.

Chinese fir and *Uncaria* particles differ in species and morphology; their heat/mass-transfer and stress–strain characteristics therefore vary. Larger particles, for instance, release steam more slowly and require longer pressing times, leading to flatter VDP curves. In this study, however, the particle dimensions of both materials were small, so these effects were relatively minor.

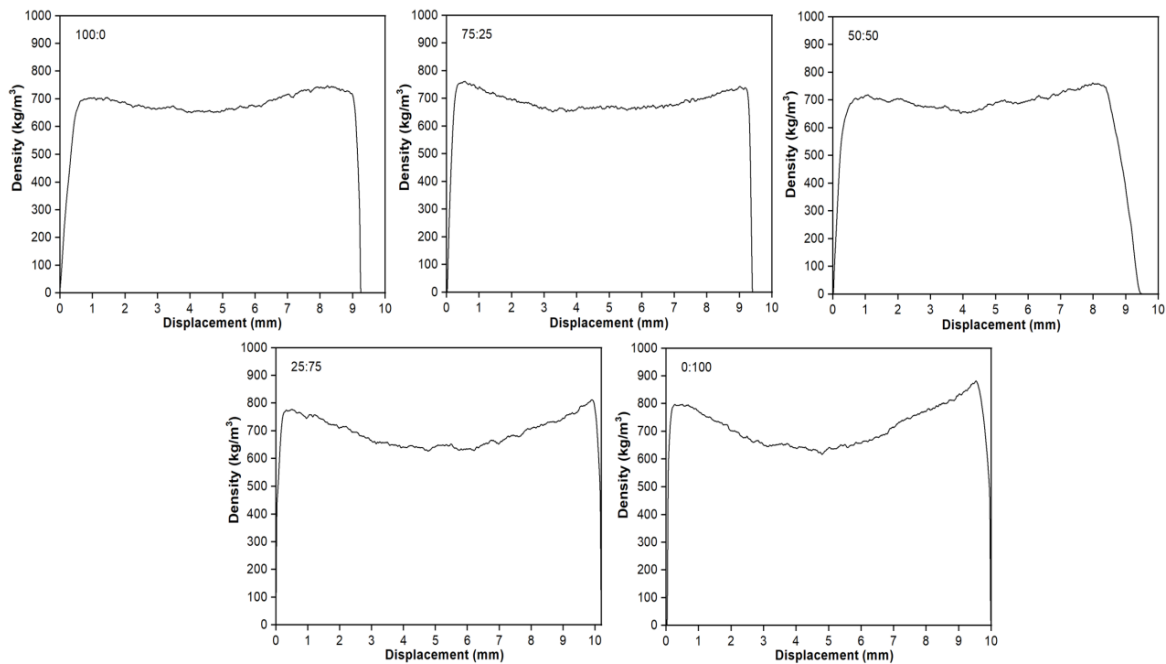


Fig. 2. The vertical density profile of particleboards

Mechanical Properties Analysis

As shown in Fig. 3, the nail-holding strength of pure Chinese fir particleboard reached 154.8 N/mm, whereas that of pure *Uncaria* particleboard was 119.8 N/mm. When the two furnish types were combined, the nail-holding strength of the composite boards varied markedly with the mixing ratio. Specifically, at a mass ratio of 75:25 the strength was 155.9 N/mm; at 50:50 it peaked at 170.8 N/mm; and at 25:75 it declined to 160.7 N/mm. Thus, increasing the proportion of *Uncaria* particles first raised and then lowered the nail-holding strength, with the maximum occurring at the 50:50 ratio.

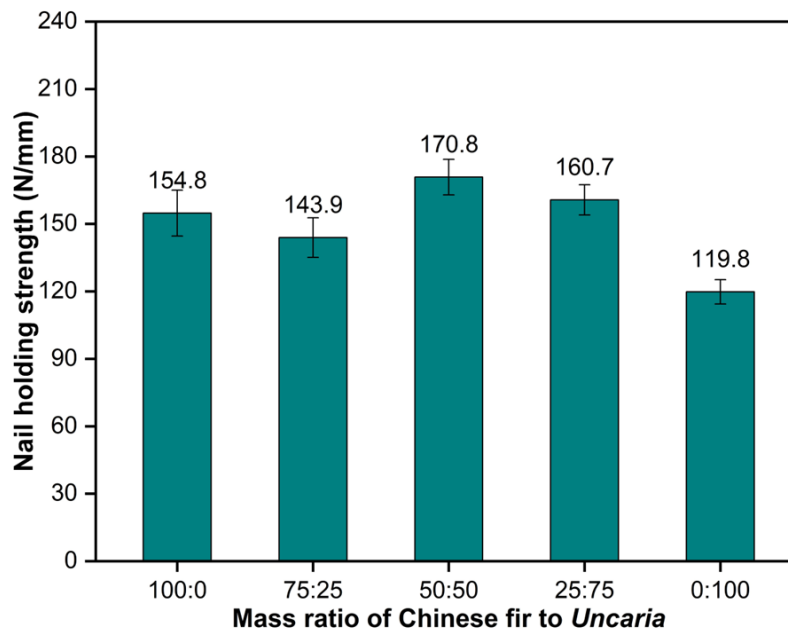


Fig. 3. Nail-holding strength test results of the particleboards

This trend is governed by several interacting factors. First, nail-holding strength is fundamentally determined by inter-particle bond strength, which in turn is strongly influenced by the intrinsic characteristics of the raw materials (Teng *et al.* 2020; Khai and Young 2022; Xu *et al.* 2025). From a chemical standpoint, *Uncaria* branches contain esters, terpenes, carboxylic acids, and alkaloids. As the *Uncaria* content rises, these specific compounds can alter the curing rate and quality of the MUF resin, eventually leading to a drop in nail-holding strength (Zhang *et al.* 2025). Second, the two furnish types differ in water absorption and in the way the adhesive penetrates their surfaces. This disparity can drive preferential adhesive flow into one species, creating local resin starvation. Finally, uneven steam diffusion during hot-pressing lowers the degree of cross-linking of the adhesive and can disrupt the bond line, further impairing nail-holding performance.

Antifungal Performance Analysis

Figure 4 visually illustrates the antifungal efficacy of particleboards with different *Uncaria* substitution levels. Pure Chinese-fir boards exhibited almost 100% mold coverage, starkly exposing the species' "triple-promotion" mechanism: (i) abundant starch and soluble sugars provide ample carbon for fungi; (ii) highly porous fiber lumina and vessel networks create expressways for hyphal penetration and lateral spread; (iii) high hygroscopicity maintains a persistently humid micro-environment that is ideal for spore germination.

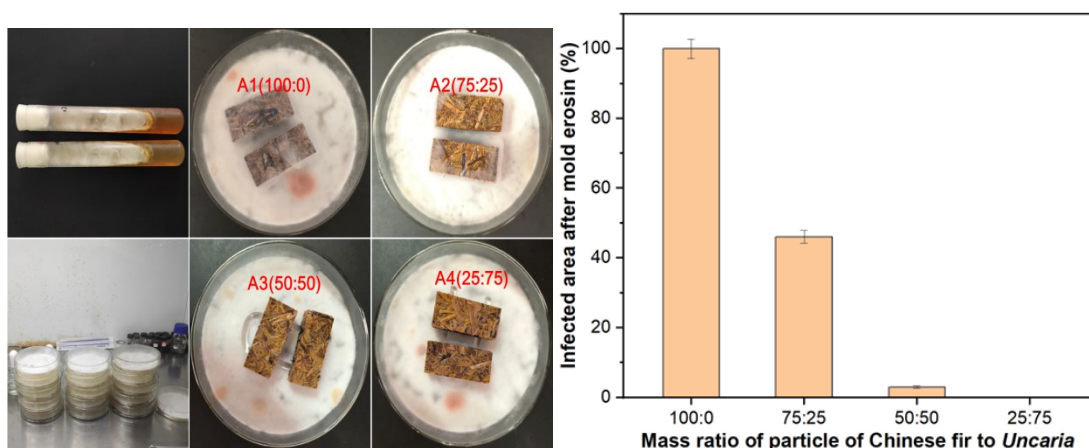


Fig. 4. Antifungal performance results of the particleboards

Upon the introduction of *Uncaria*, fungal colonization receded in a precise, dose-dependent manner, marked by a consistently reproducible threshold. These findings provide evidence that this antifungal efficacy is no accident, but rather are the deliberate outcome of *Uncaria*'s combined chemical arsenal and physical armor. At 25% substitution, infection area plunged from 100% to 46% (a 54% reduction). At this stage, low concentrations of *Uncaria*-derived alkaloids and volatile terpenes were sufficient to block spore germination and retard hyphal elongation. At 50% substitution, residual infection fell to only 3%—essentially mold-free—because active compounds now occupied every potential nutrient site on the fir surface, forming a continuous chemical shield. At 75% substitution, no mold was detected, achieving complete protection.

If the antifungal efficacy of the composite boards were to be attributed to anything, it would be a multi-component, three-dimensional defense system rather than a single compound. Alkaloids insert into fungal membrane phospholipid bilayers, disrupting

membrane potential and ergosterol synthesis, leading to loss of membrane integrity and collapse of hyphal tips. Terpenes and esters act as hydrophobic tails that penetrate the lipid bilayer while their hydrophilic heads chelate intracellular Ca^{2+} , Mg^{2+} , and Fe^{2+} ions, triggering lipid-peroxidation cascades. Carboxylic acids rapidly lower substrate pH and sequester essential micronutrients (Fe^{3+} , Zn^{2+}), inhibiting extracellular cellulases, laccases, and amylases (Geng *et al.* 2019; Hu 2024). Additionally, *Uncaria* fibers are stiffer and lignin-rich; their incorporation raises board density and reduces porosity, limiting moisture, and oxygen diffusion to create an effective physical barrier. The phenolic hydroxyl groups in lignin also scavenge free radicals, providing antioxidant synergy that further suppresses mold (Wu *et al.* 2021; Yu *et al.* 2021).

Decay Resistance Analysis

The decay test illustrated in Fig. 5 further elucidates how *Uncaria* branch content influenced the durability of composite particleboards. White-rot fungi preferentially secrete laccase, manganese peroxidase, and lignin peroxidase, selectively oxidizing and cleaving the three-dimensional lignin network. This rapidly bleaches the originally yellow-brown fir, thins the cell walls and, once the lignin shield is breached, allows cellulases and hemicellulases to attack the exposed microfibrils, ultimately causing mass loss and mechanical collapse. After 12 weeks of white-rot exposure, pure Chinese-fir particleboards exhibited a mass loss of 35.8%, well above the Grade-II durability limit ($\leq 30\%$) specified in GB/T 13942.1 (2009).

Introducing 25% *Uncaria* particles abruptly reduced mass loss to 29.0%, a 6.8% improvement, indicating that even a low dose of *Uncaria* exerts a chemical interception on decay fungi. *Uncaria* alkaloids and terpenes bind to the enzyme active sites and chelate the essential co-factors $\text{Fe}^{2+}/\text{Mn}^{2+}$ ions, thereby curtailing extracellular enzyme activity and interrupting the lignin-radical chain reaction. Yet, with fir still dominating the substrate, the reduction remains modest.

At the 50% substitution level, mass loss declined only marginally to 28.8%, and the curve flattened. A further increase to 75% *Uncaria*, however, drove mass loss down to 25.7% — an overall reduction of 10.1% points. This pronounced improvement stems from a triple synergy: (1) carboxylic acids chelate metal ions, blocking the Fenton reaction and suppressing free-radical side-chain cleavage of lignin aromatic rings; (2) the readily degradable fir fraction is effectively diluted, directly reducing the total carbon available to fungi; and (3) board density rises and porosity falls, lowering the oxygen and moisture diffusion coefficients and markedly increasing the resistance to hyphal penetration.

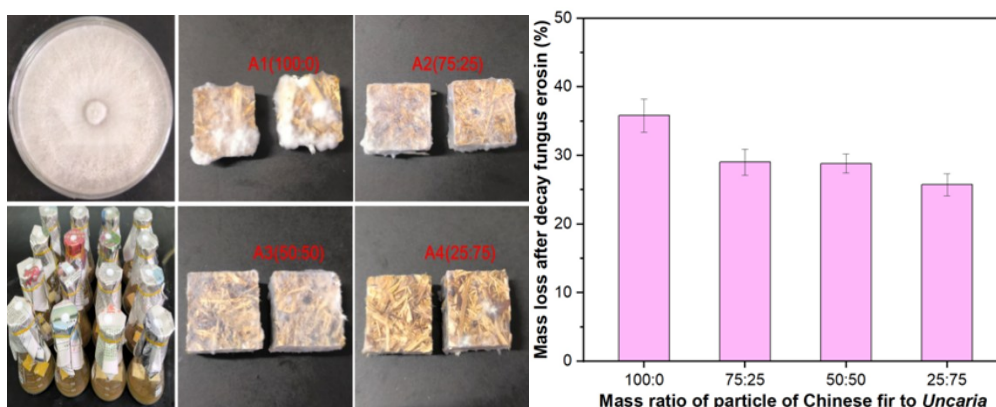


Fig. 5. Decay resistance test results of the particleboards

Termite Resistance Analysis

Figure 6 presents the one-month termite attack results for the particleboards. Pure Chinese-fir boards suffered a mass loss as high as 18.2%, whereas stepwise increases in *Uncaria* branch incorporation reduced the losses to 12.2%, 10.1%, and 7.5%, respectively. This linear suppression indicates that the termites' "preference" for fir was progressively counteracted by *Uncaria*.

Indole alkaloids and terpenes in *Uncaria* impart an intense bitter and pungent taste to the insects' chemoreceptors, disrupting neural transmission and markedly decreasing feeding frequency (Vargas-Ortiz *et al.* 2018). The alkaloids also chelate $\text{Fe}^{2+}/\text{Zn}^{2+}$ ions, inhibiting key enzymes of the termites' symbiotic protozoa and forcing a reduction in food intake. Volatile terpenes continuously emanate from the board surface, creating an olfactory barrier that interferes with pheromone recognition and lowers the number of exploratory contacts by worker termites. The heightened density and hardness of the board can markedly elevate the specific cutting energy, thereby impeding the forward progress of the insect's tunnel. Simultaneously, the denser structure reduces water activity, indirectly suppressing protozoan activity within the termites' gut. Finally, the readily degradable polysaccharides of fir are diluted by *Uncaria* lignin and extractives, sharply decreasing the total carbon source and preventing termites from obtaining sufficient nutrition within the limited time frame.

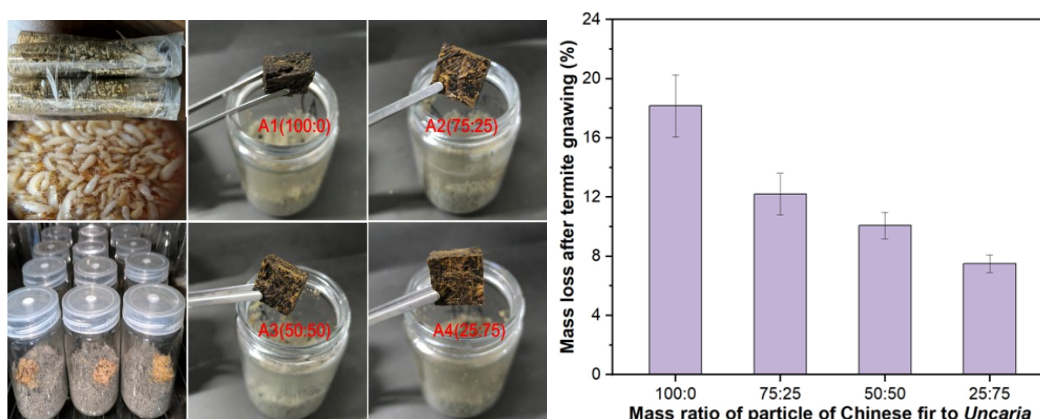


Fig. 6. Termite resistance test results of the particleboards

Flame-retardancy Analysis

Figure 7 compares the fire performance of pure Chinese-fir particleboard and the composite board containing 75% *Uncaria* substitution. Cone-calorimetry data, interpreted at both macro- and micro-scales, reveal a pronounced improvement imparted by *Uncaria* branches. Pure fir board ignited within 18 s under 50 kW/m² irradiation; its peak heat-release rate (pk-HRR) reached 390 kW/m² and the average HRR (av-HRR) was 181 kW/m². The char residue was < 5%, leaving loose, grey-white ash with no coherent char layer. In contrast, the fir-*Uncaria* composite exhibited a pk-HRR of 372 kW/m², an av-HRR of 152 kW/m², an ignition delay of 22 s, and a char yield of 11%, accompanied by an intumescent, blistered char shell.

The leap in flame retardancy is intimately linked to the unique chemical "fingerprint" of *Uncaria* branches. The synergistic mechanism can be rationalized in three dimensions:

- (1) Gas-phase radical quenching – During pyrolysis at 280 to 320 °C, *Uncaria*

alkaloids undergo Hofmann elimination and dealkylation, releasing NH_3 , HNCO , and highly reactive $\text{N}^\cdot$ and $\text{NH}^\cdot$ radicals. These nitrogen-centered species terminate the $\cdot\text{H}/\cdot\text{OH}$ chain reactions at the flame front, lowering radical concentrations. Concurrently, terpene scission produces CO_2 and H_2O , diluting combustible volatiles and depressing flame temperature.

(2) Condensed-phase char formation – Phenolic hydroxyls in lignin and carboxylic acids jointly catalyze dehydration and condensation, driving aromatization and cross-linking to generate a three-dimensional, porous carbon scaffold. The expanded char layer increases the insulation thickness and reduces its thermal conductivity.

(3) Structural-phase densification – The stiffer, lignin-rich *Uncaria* fibres raise board density and lower porosity, cutting the oxygen diffusion coefficient and decoupling fuel–oxygen interactions. This extends ignition time by 4 s and slashes av-HRR by 16%.

In summary, through a three-dimensional synergy of gas-phase radical capture, condensed-phase intumescent char, and structural-phase dense barrier, *Uncaria* branches upgrade Chinese-fir particleboard from readily combustible to GB/T 8624 (2012) Class B1, offering a theoretical basis for green flame-retardant wood composites.

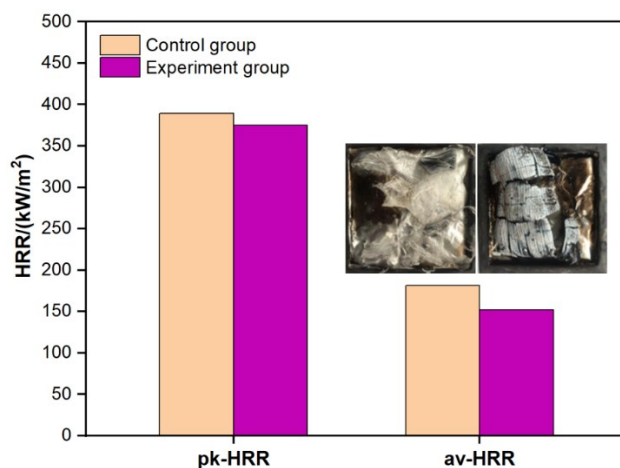


Fig. 7. Flame-retardancy test results of the particleboards

CONCLUSIONS

1. *Uncaria* branches contain 19 bioactive constituents—dominated by esters, terpenes, carboxylic acids, and indole alkaloids—that confer multifaceted protection on the composite boards. These compounds chelate metal ions, quench free radicals, disrupt insect pheromone recognition, and catalyze char formation, collectively enhancing mold resistance, decay resistance, insect resistance, and flame retardancy.
2. When the mass ratio of Chinese fir to *Uncaria* is 50:50, the composite particleboard attained its maximum nail-holding strength (170.8 N/mm), striking an optimal balance between mechanical performance and functional upgrading.
3. Replacing 75% of fir with *Uncaria* transformed the board from “non-durable, non-insect-resistant, readily combustible” to “Grade-II decay resistance, Grade 8–9 termite resistance, and Class B1 flame retardancy”. Mass loss, mold coverage, and peak heat-release rate (pk-HRR) were reduced by 28%, 97% and 4.6%, respectively, achieving a superior equilibrium between mechanical and durability properties.

4. Valorizing *Uncaria* waste branches not only solves their disposal problem but also provides Chinese-fir particleboard with a “one-dose, multi-effect” green modification strategy, markedly decreasing the need for chemical preservatives and flame retardants. The approach offers compelling economic and environmental benefits and is ready for industrial-scale deployment.

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REFERENCES CITED

- Bakir, D., Dogu, D., and Kartal, S. (2021). “Anatomical structure and degradation characteristics of bioincised oriental spruce wood by *Physisporinus vitreus*,” *Wood Material Science and Engineering* 1, 1-12. DOI: 10.1080/17480272.2021.1964594.
- Cavdar, A. (2014). “Effect of various wood preservatives on limiting oxygen index levels of fir wood,” *Measurement* 50, 279-284. DOI: 10.1016/j.measurement.2014.01.009
- Fernandez-Costas, C., Palanti, S., Charpentier, J.-P., and Sanroman, M. A. (2017). “A sustainable treatment for wood preservation: Enzymatic grafting of wood extractives,” *ACS Sustainable Chemistry and Engineering* 5(9), 7557-7567. DOI: 10.1021/acssuschemeng.7b00714
- Fu, L. (2015). *Chemical Constituents and their Biocontrol Activities from Three Medicinal Plants*, Master's Thesis, Nanjing Agricultural University, China.
- Geng, C., Yang, T., Huang, X., Ma, Y., Zhang, X., and Chen, J. (2019). “Antidepressant potential of *Uncaria rhynchophylla* and its active flavanol, catechin, targeting melatonin receptors,” *Journal of Ethnopharmacology* 232, 39-46. DOI: 10.1016/j.jep.2018.12.013
- Guo, Q., Si, X., Shi, Y., Yang, H., Liu, X., Liang, H., Tu, P., and Zhang, Q. (2019). “Glucosylated monoterpene indole alkaloids from *Uncaria rhynchophylla*,” *Journal of Natural Products* 82(12), 3288-3301. DOI: 10.1021/acs.jnatprod.9b00490
- GB/T 14018 (2009). “Method of testing nail holding power of wood,” Standardization Administration of China, Beijing, China.
- GB/T 18261 (2013) “Method for evaluating the efficacy of mold inhibitors against wood molds and stain fungi,” Standardization Administration of China, Beijing, China.
- GB/T 13942.1 (2009). “Durability of wood—Part 1: Laboratory method for determining natural decay resistance,” Standardization Administration of China, Beijing, China.
- GB/T 8624 (2012). “Classification for burning behavior of building materials and products,” Standardization Administration of China, Beijing, China.
- Hu, T. (2024). *Analysis of Uncaria Alkaloid Synthesis Pathway-based on Uncaria*

- Rhynchophylla* Genome, Master's Thesis, Guizhou University, China.
- Jin, X. (2022). "Effects of logging on the trade-off between seed and sprout regeneration of dominant woody species in secondary forests of the Natural Forest Protection Project of China," *Ecological Processes* 11(1), article ID 363. DOI: 10.1186/s13717-022-00363-3
- Khai, T. D., and Young, J. G. (2022). "Withdrawal capacity and strength of self-tapping screws on cross-laminated timber," *Structures* 37, 772-786. DOI: 10.1016/j.istruc.2022.01.033
- Li, D., Yu, L., Li, L., Liang, J., Wu, Z., Xu X., Zhong, X., and Gong, F. (2023). "Melamine-urea-formaldehyde resin adhesive modified with recycling lignin: Preparation, structures and properties," *Forests* 14(8), article 1625. DOI 10.3390/f14081625
- Li, D., Yu, L., Li, L., Liang, J., Wu, Z., Yang, G., Yin, S., and Gong, F. (2024). "Comparison of nail-holding performance of *Pinus massoniana* and *Cunninghamia lanceolata* dimension lumber based on round steel nails," *BioResources* 19(1), 670-682. DOI: 10.15376/biores.19.1.670-682
- Teng, Q. C., Wang, F. B., Que, Z. L., and Zeng, N. (2020). "Effects of angles on the screw and nail withdrawal strength in dimension lumber," *Scientia Silvae Sinicae* 56(1), 154-161. DOI: 10.11707/j.1001-7488.20200115
- Vargas-Ortiz, E., Gonda, I., Smeda, J., Mutschler, M., Giovannoni, J., and Jander, G. (2018). "Genetic mapping identifies loci that influence tomato resistance against Colorado potato beetle," *Scientific Reports* 8, article ID 7429. DOI:10.1038/s41598-018-24998-5.
- Wang, F., Liu, J., and Lyu, W. (2019). "Effect of boron compounds on properties of Chinese fir wood treated with PMUF resin," *Journal of Bioresources and Bioproducts* 4(1), 60-66. DOI: 10.21967/jbb.v4i1.182
- Wang, J., Xing, Y., Chang, X., Yang, H., Yang, C., Xue, G., and Li, C. (2024). "Identification of priority conservation areas for natural forest protection project in Northeastern China based on OWA-GIS," *Ecological Indicators* 160, article 111718. DOI: 10.1016/J.ECOLIND.2024.111718
- Wozniak, M. (2022). "Antifungal agents in wood protection—A review," *Molecules* 27(19), article 6392. DOI: 10.3390/molecules27196392
- Wu, Z., Deng, X., Luo, Z., Zhang, B., Xi, X., Yu, L., and Li, L. (2021). "Improvements in fire resistance, decay resistance, anti-mold property and bonding performance in plywood treated with manganese chloride, phosphoric acid, boric acid and ammonium chloride," *Coatings* 11(4), article ID 399. DOI 10.3390/coatings11040399
- Xi, X., Wu, Z., Pizzi, A., Gerardin, C., Lei, H., Zhang, B., and Du, G. (2019). "Non-isocyanate polyurethane adhesive from sucrose used for particleboard," *Wood Science and Technology* 53(2), 393-405. DOI: 10.1007/s00226-019-01083-2
- Xu, X., Li, D., Yang, S., Wu, L., Yang, Q., Yang, H., Yang, X., Zhang, Q., Yu, L., and Wu, Z. (2025). "Effects of intersection angle on the nail-holding performances of *Pinus massoniana* and *Cunninghamia lanceolata* dimension lumber," *BioResources* 20(2), 3576-3586. DOI: 10.15376/biores.20.2.3576-3586
- Yan, K., Wang, W., Li, Y., Wang, X., Jin, J., Yang, H., and Wang, L. (2022). "Identifying priority conservation areas based on ecosystem services change driven by natural forest protection project in Qinghai province, China," *Journal of Cleaner Production* 362, article 132453. DOI: 10.1016/j.jclepro.2022.132453
- Yang, R., Jari, K., Anne, T., Shunbo, Y., Sami, B., Heimo, K., Caixia, X., and Liu, Y.

- (2018). “The effect of China's new circular collective forest tenure reform on household non-timber forest product production in natural forest protection project regions,” *Sustainability* 10(4), 1091-1091. DOI: 10.3390/su10041091
- Yu, L., Luo, Z., Li, L., Xi, X., Wu, Z., and Zhang B. (2021). “Study of burning behaviors and fire risk of flame-retardant plywood by cone calorimeter and TG test,” *Journal of Renewable Materials* 9(12), 2143-2157. DOI: 10.32604/jrm.2021.016092
- Zhan, J. (2022). *Study on Uncaria Stem Extract as Corrosion Inhibitor for Hydrochloric Acid Picking of Carbon Steel*, Master’s Thesis, Harbin Institute of Technology, China.
- Zhang, B., Yu, L., Zhang, Q., Li, D., Tu, Y., Xiao, G., Wu, Z., and Liang, J. (2022). “Effects of fire retardants on mechanical properties and water resistance of *Pinus massoniana* particleboard,” *Wood Research* 67(3), 411-422. DOI: 10.37763/wr.1336-4561/67.3.411422
- Zhang, Q., Wu, L., Liao, H., Yang, Q., Yang, H., Yang, Y., He, X., Lan, L., Li, D., and Wu, Z. (2025). “Performance of *Cunninghamia lanceolata*/*Uncaria* composite particleboard,” *BioResources* 20(1), 1738-1754. DOI: 10.15376/biores.20.1.1738-1754
- Zhong, X., Li, D., Xu, X., Li, Q., Yu, D., Wu, Z., Liang, J., Peng, J., Gu, W., Zhao, X., Yin, S., Yang, G., and Gong, F. (2024). “Effects of dowel rotation welding conditions on connection performance for Chinese fir dimension lumbers,” *Forests* 15(6), article 1038. DOI: 10.3390/f15061038

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