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RESEARCH PROGRESS IN SILICIFICATION MODIFICATION OF WOOD. REVIEW

HONGWEI FAN[1, 2], MIN LI[2], XINWEI TU[1,2], LIN YANG[1]
[1]NAN JING FORESTRY UNIVERSITY, PR CHINA
[2]CHINESE ACADEMY OF TROPICAL AGRICULTURAL SCIENCES
CHINA

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ABSTRACT

Wood is prone to decay, flammability and poor dimensional stability, which restrict its high-value application in furniture manufacturing, architectural decoration and other fields. As an advanced wood modification technology, wood silicification modification can significantly improve wood properties by impregnating silicon-based precursors into the interior of wood and forming SiO_2 in situ. This paper reviews the latest research progress of wood silicification modification, elaborates on the structural characteristics of two types of silicon sources (organic and inorganic), sorts out the key points of current mainstream silicification processes, and analyses the improvement effects of wood silicification modification on wood properties such as dimensional stability, decay resistance and flame retardancy. It is proposed that future research is going to focus on the development of green and efficient new technologies and the exploration of organic-inorganic interface regulation mechanisms, aiming to develop multi-functional intelligent silicified wood.

KEYWORDS: Wood, silicification modification, wood properties.

INTRODUCTION

When wood is buried in silicon-rich strata under specific geological conditions, soluble silicic acid (e.g., H_4SiO_4) in soils gradually infiltrates into the wood structure. Following millions of years of replacement and filling, organic components such as cellulose and hemicellulose are progressively substituted by SiO_2, ultimately resulting in the formation of silicified wood (Liu et al. 2025, Mustoe 2017, Mai and Militz 2004, Doubek et al. 2018). Silicified wood retains the original anatomical structure of wood, and exhibits significantly superior properties including high hardness, excellent dimensional stability, and decay resistance compared with natural wood.

Inspired by natural silicified wood, researchers have carried out extensive studies on wood silicification modification since the early 1990s (Götze et al. 2008). Using sol-gel and other methods, SiO_2 is introduced into wood cell lumens and cell walls to prepare high-performance wood-based composites with excellent and versatile properties. After decades of development, the performance and functionality of artificial silicified wood have been significantly improved. This paper reviews the recent progress in wood silicification modification, summarizes silicon sources, preparation processes, material properties and modification mechanisms, and prospects future development trends and application potentials.

Inorganic silicon sources

Sodium silicate

Sodium silicate exhibits excellent water solubility, and its aqueous solution is commonly known as water glass, which holds significant application value in wood hardening and flame retardancy (Liu et al. 2019, Ma et al. 2025, Li et al. 2020). Its chemical formula is $Na_2O\cdot nSiO_2$, where n denotes the modulus. A higher modulus corresponds to a higher viscosity and lower water solubility of sodium silicate, whereas a lower modulus results in a lower viscosity and higher water solubility (Wang et al. 2023, Li et al. 2020, Yona et al. 2021). Upon impregnation into wood, sodium silicate hydrolyses to form polysilicic acid, which reacts with -OH groups on the wood cell wall to form Si-O-C bonds. Meanwhile, sodium silicate transforms into silica gel during drying and curing, which further dehydrates into SiO_2 and fills the wood pores, thereby improving the overall performance of wood (Bi et al. 2023, You et al. 2025).

However, sodium silicate solution is alkaline, and prolonged impregnation treatment can induce the degradation of cellulose and hemicellulose in wood (Zhou et al. 2020). During the penetration process, sodium silicate causes swelling in the amorphous regions and disturbs the well-ordered microfibril structure within crystalline regions, thereby reducing the crystallinity of wood. In addition, previous studies have confirmed that sodium silicate can react with hydroxyl groups in wood, destroy hydrogen bonds of cellulose and weaken the interaction between cellulose molecular chains, which also leads to the decline of crystallinity (Kuai et al. 2022). Therefore, the adverse effect of sodium silicate on wood crystallinity should be fully considered in wood modification to prevent the deterioration of mechanical properties.

Nano-SiO_2

Nano-SiO_2 refers to SiO_2 particles with a size range of 1-100 nm. Due to its large specific surface area, good dispersibility and high chemical stability, it has been widely used in coatings, polymers and other industrial fields (Wang et al. 2014, Bhatt et al. 2021, Zhang et al. 2022). Moreover, nano-SiO_2 particles exhibit high strength, high rigidity and excellent thermal stability. When incorporated into wood, they can effectively enhance the mechanical strength and thermal stability of wood (Zahng et al. 2019). Nano-SiO_2 is also often combined with resins for wood modification (Venkatesan et al. 2022, Nagraik et al. 2025, Dong et al. 2015). Nanotechnology provides a new research direction for wood modification, and even a small amount of nano-SiO_2 can significantly improve the properties of wood.

Silica sol

Silica sol is a colloidal solution in which SiO_2 particles are uniformly dispersed in water or organic solvents. It presents as a pale white emulsion with the characteristics of low viscosity, small particle size, non-toxicity and odorlessness (Huang et al. 2026, Li et al. 2023). SiO_2 particles in silica sol possess abundant surface -Si-OH groups. After penetrating wood pores, they bond with each other and react with -OH groups on wood cell walls. During drying and curing, condensation forms a three-dimensional SiO_2 gel network cross-linked with the wood matrix, thus improving wood performance (Xu et al. 2020, Jiang et al. 2021, Lu et al. 2014). At present, the main preparation methods of silica sol are shown in Tab. 1.

Tab. 1: The main preparation methods of silica sol.

Methods	Preparation process	Characteristics
Stöber method	In alcohol solvents, using ammonia as a catalyst, TEOS is first hydrolysed to form silicic acid, which then condenses to generate uniform SiO_2 nuclei. By controlling the reaction conditions to promote the synchronous growth of these nuclei, silica sol with uniform particle size and controllable dimensions can be obtained (Stöber et al. 1968, Rahman et al. 2007).	The prepared SiO_2 particles have good monodispersity, small and narrowly distributed particle size, and low impurity content, but the cost is relatively high, making it unsuitable for large-scale production (Cai et al. 2019, Tadanaga et al. 2013).
Ion exchange method	Sodium silicate was passed through a cation-exchange resin to remove sodium ions, yielding active silicic acid. The silicic acid further polycondensed to form nano-SiO_2 particles. Finally, the sol was concentrated by evaporation or ultrafiltration, and the pH was adjusted to alkaline to obtain stable silica sol (Song et al. 2025).	It features low cost and is suitable for large-scale production, but requires high energy consumption for post-treatment (Zheng et al. 2010, Li et al. 2023).
One-step dissolution method of elemental silicon	Silica sol is directly prepared by heating and dissolving silicon powder in water under the action of a catalyst (Huang et al. 2010).	The process is simple, the particle size is easy to control, and the stability is good, but the raw material cost and processing energy consumption are high (Zheng et al. 2010).
Electrodialysis method	Electrolytic electrodialysis reaction is carried out by adding electrolyte solution into an electrolytic cell equipped with suitable electrodes. Silica sol is prepared by adjusting the pH of the electrolyte and controlling reaction conditions such as current density and temperature (Marsálek et al. 2019).	The product has high purity and low impurity content, but requires high equipment investment and high energy consumption (Li et al. 2023).
Dispersion method	Silica sol is formed by mechanically dispersing silicon dioxide microparticles in water.	The process is simple, but the product exhibits poor uniformity and low purity.

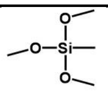
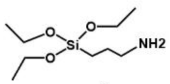
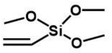
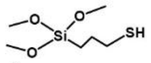
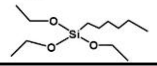
Organic silicon sources

Silane coupling agent

Silane coupling agents (SCA), referred to as silanes, have the general formula Y-$(CH_2)_n$-X represents hydrolysable groups, such as alkoxy groups ($-OCH_3$, $-OC_2H_5$, etc.), which are highly sensitive to moisture and can undergo hydrolysis to form highly reactive -Si-OH groups. These silanol groups can further condense with -OH groups on the surface of inorganic materials (silica, metal oxides, etc.) to form stable Si-O-M bonds (*M* denotes inorganic matrix). Y is an organic functional group, such as vinyl ($-CH=CH_2$), epoxy group (-CH(O)CH-), etc.

Such functional groups can react with organic polymers (resins, rubbers, etc.) or form physical interpenetrating networks, thereby achieving firm bonding (Aziz et al. 2021, Yu et al. 2021, Zhou and Xu 2022, Liu et al. 2019, Zhao et al. 2023).With its bifunctional groups capable of forming chemical bonds with organic and inorganic substances respectively, it is frequently employed to enhance the interfacial bonding between organic and inorganic phases (Chen et al. 2017, Zhang et al. 2022, fang et al. 2014, Hafezi et al. 2016). Liu et al. (2020) modified the surface of birch substrates with KH570 to achieve high adhesion of UV-curable inks on wood surfaces. The bond strength of the modified wood surface reached 5.91 MPa, which was an increase of 354.62% compared with untreated wood. With continuous development by researchers, hundreds of silane coupling agents have been developed and can be classified into various types. The commonly used silane coupling agents are listed in Tab. 2.

Tab. 2: Common silane coupling agents.

Full chemical name	Abbreviation	CAS	Molecular formula	Structural formula
Methyltrimethoxysilane	MTMS	1185-55-3	$C_4H_{12}O_3Si$	
Aminopropyltriethoxysilane	APTES	919-30-2	$C_9H_{23}NO_3Si$	
Vinyltrimethoxysilane	VTMS	2768-02-7	$C_5H_{12}O_3Si$	
Mercaptopropyltrimethoxysilane	MPTMS	4420-74-0	$C_6H_{16}O_3SSi$	
Octyltriethoxysilane	OTES	2943-75-1	$C_{14}H_{32}O_3Si$	

Silicone oil

Silicone oil is a linear polysiloxane liquid at room temperature, which is colourless or light yellow, water-insoluble, non-toxic, odourless and thermally stable. It is mainly divided into methyl silicone oil and modified silicone oil. The former, containing only methyl groups, is the most common, while the latter is obtained by substituting some methyl groups to improve performance. Silicone oil is often used as a heating medium in heat treatment to enhance dimensional stability and reduce hygroscopicity (He et al. 2020, Qian et al. 2018, Okon et al. 2017, Mastouri et al. 2021). Meanwhile, silicone oil can penetrate into the interior of wood and block its pores, thus restraining the movement and transport of moisture (He et al. 2019).

Silicone resin

Silicone resin is a type of polysiloxane with a Si-O-Si main chain, in which organic groups are attached to silicon atoms in the framework, forming a highly cross-linked three-dimensional network structure. According to the types of organic groups, silicone resins can be classified into methyl-based, phenyl-based, amino-based, and other types. These organic groups determine the properties of different silicone resins: methyl groups improve the flexibility of polymer segments, while rigid groups such as phenyl groups enhance the mechanical properties and thermal stability of the material (Zhang et al. 2021, Robeyns et al. 2018). In practical applications, silicone resins are often coated on wood surfaces as protective coatings to improve the weather resistance and water resistance of wood (Slabejova et al. 2018).

Methods of wood silicification

Vacuum-pressure impregnation

Wood is a porous material, and modifiers can penetrate into its interior through vessels, pits, and other pore structures (Plötze et al. 2011). Under atmospheric pressure, modifiers enter the pores mainly by osmotic pressure and capillary force, but the driving force is usually insufficient, resulting in shallow impregnation depth. To improve impregnation depth, most researchers adopt the "breathing method" (Wang et al. 2023, Zhang et al. 2023, Tao et al. 2024), namely vacuum-pressure impregnation, to drive modifiers into wood. Vacuum treatment effectively removes air from wood pores, facilitating more modifier uptake, while pressure treatment forces modifiers deep into the wood, increasing impregnation depth and weight percent gain. Lemaire-Paul et al. (2023) investigated the effect of SiO_2 impregnation on spruce under different vacuum pressures. They found that the diffusion depth of SiO_2 in spruce was the greatest and the impregnation effect was optimal at a vacuum pressure of -0.09 MPa.

Sol–gel method

The sol-gel method is a wet-chemical approach. Using silicon precursors (such as TEOS) as raw materials, they first hydrolyse in solution to form flowable sol, which penetrates into the wood. Further polycondensation eliminates the fluidity of the sol and forms a gel. After drying and curing, silica particles are formed inside the wood (Zhang et al. 2017, Zhou et al. 2014, Unger et al. 2013). The -Si-OH groups generated during the reaction can form hydrogen bonds or covalent bonds with the -OH groups in wood cellulose, resulting in a stronger combination between the modified layer and the wood substrate (Wang et al. 2023, Qu et al. 2021, Li et al. 2025, Götze et al. 2008, Donath et al. 2004).

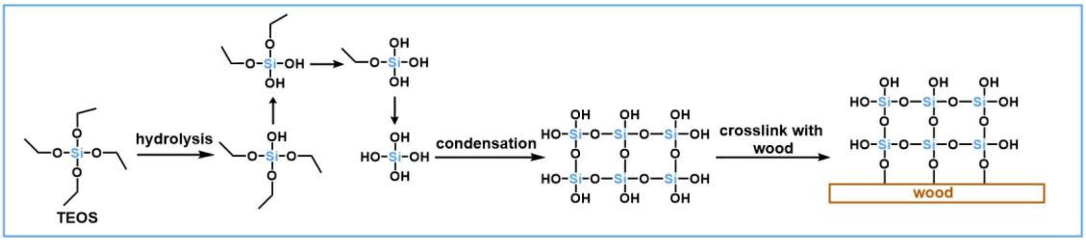


Fig. 1: Schematic diagram of sol-gel method.

Chemical vapor deposition

Chemical vapor deposition (CVD) is a material surface modification technique. Silicon-containing gaseous precursors are introduced into the reaction chamber under vacuum or specific atmospheres (e.g., nitrogen, argon), where chemical reactions occur on the wood surface to deposit a uniform and dense SiO_2 film (Li et al. 2023, Wei and Niu 2023, Yao et al. 2023). Currently, organosilanes such as TEOS and PDMS are the dominant silicon sources in CVD. Coatings prepared by CVD are uniform with controllable thickness, and have little effect on the appearance and dimensions of wood. Nevertheless, the penetration depth is limited, so CVD mainly achieves surface modification rather than bulk silicification of wood (Fu et al. 2020, Yang et al. 2020). Jian et al. (2023) deposited MTCS and PFDMS on wood surfaces via CVD. The modified wood exhibited superhydrophobic and oleophobic properties, with a water contact angle of 157.7° and an oil contact angle of 141.3°. Moreover, the coating showed excellent mechanical properties and chemical stability, enabling long-term service in harsh outdoor environments.

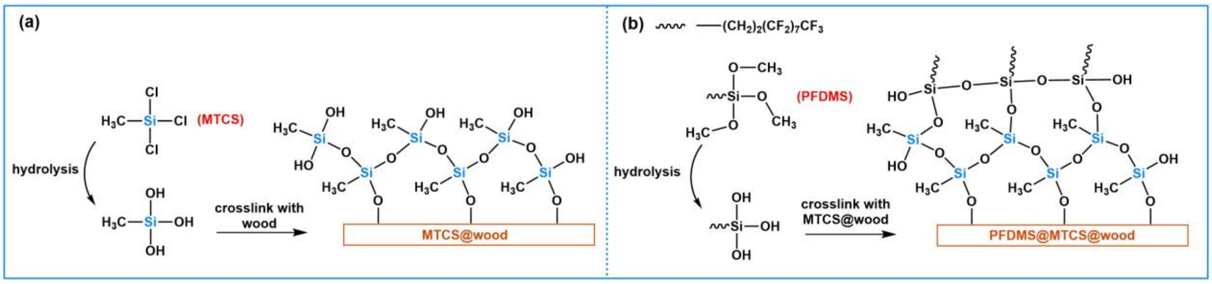


Fig. 2: Schematic diagram of the preparation of MTCS@wood and PFDMS@MTCS@wood.

Properties and mechanism of wood silicification treatment

Dimensional stability

The shrinkage and swelling behaviour of wood is the main cause of its dimensional instability. Therefore, improving the dimensional stability of wood requires reducing the ability of -OH groups in wood to bind with water molecules (Sargent 2019, Yin et al. 2023, Wei et al. 2017, Schorr and Blanchet 2020). Zhang impregnated heat-treated rubberwood with TEOS and compared it with untreated wood. They found that the tangential and radial dimensional swelling rates were reduced by 52.48% and 39.47%, respectively, whereas only heat-treated rubberwood showed reductions of 35.33% and 10.53%. The reason was that after TEOS modification, the number of -OH groups on the cell wall decreased, weakening the binding ability with water molecules and thus lowering the swelling capacity of the cell wall (Zhang et al. 2019). Bak et al. (2022) synthesized microporous SiO_2 aerogels in situ within beech and Scots pine wood via the sol-gel method, which reduced the affinity of water toward cell wall components. Their results showed that the ASE in the radial and tangential directions of the modified beech wood reached 39.64% and 26.49%, respectively, while those of the modified Scots pine wood were 35.17% and 23.10%, respectively.

Mechanical properties

Some wood species, especially fast-growing wood, have disadvantages such as low density, soft texture, and low strength (Komán et al. 2023, Liu et al. 2024, Rahayu et al. 2020). Following silicification modification, SiO_2 fills and coats the wood cell lumens and cell walls. Acting as a skeleton, SiO_2 supports the wood's porous structure, forms strong interfacial bonding and mechanical interlocking with cellulose chains, and shares stress, thus enhancing the mechanical properties of wood (Xu et al. 2020, Liu et al. 2023, Jiang et al 2022, Danilov et al. 2021). Li et al. (2023) used chitosan as a mineralization inducer and formed a chitosan-SiO_2 film on wood surface via the layer-by-layer self-assembly method and sol-gel method. The results showed that the flexural strength of mineralized wood increased from 80.2 MPa to 140.0 MPa, and the modulus of elasticity increased from 7721 MPa to 12510 MPa. Yang et al. (2023) mixed non-ionic surfactant (fatty alcohol polyoxyethylene ether) with silica sol to enhance the penetration of silica sol into wood. Experimental results indicated that the flexural strength and flexural modulus of elasticity of the modified wood were improved by 79.7% and 89.5% compared with untreated wood, respectively.

Flame retardancy

Wood is flammable, posing fire hazards in applications. Silicification modification introduces silicon-based substances to form a stable SiO_2 ceramic layer within wood. This inorganic layer insulates oxygen and heat, suppresses flammable volatile release, and facilitates the formation of a compact char layer, thereby slowing combustion and realizing flame retardancy (Xu et al. 2025, Wang et al. 2023, Song et al. 2025, Liu et al. 2020, He et al. 2017, Wei et al. 2024, Gong et al. 2022, Zhang and Xu 2019). Pan et al. (2014) prepared wood fibre-high density polyethylene composites (WPCs) with nano-SiO_2 and ammonium polyphosphate (APP). WPCs containing 8% APP and 6% nano-SiO_2 exhibited the best thermal stability and flame retardancy. Compared with the untreated group, the average and peak heat release rates decreased by 42% and 44%, respectively, and the ignition time was extended by 78%. Kačíková et al. (2021) employed three types of nanoparticles (TiO_2, SiO_2, ZnO) together with sodium silicate to improve the fire resistance of oak wood. Thermogravimetric analysis showed that sodium silicate significantly reduced the thermal decomposition temperature of wood. Combined treatment with sodium silicate and nanoparticles accelerated wood decomposition and non-combustible gas release, thus delaying the combustion process.

Decay resistance

Wood is susceptible to decay by fungi and insects during service, especially in outdoor environments. Preservative treatment of wood can effectively prevent biological erosion and extend its service life (Yan et al. 2021, Kartal et al. 2009). Pries and Mai (2013) added 2% cationic silica sol to malt-agar growth medium and found that the growth of 40-50% of wood-rotting fungi was inhibited, whereas other types of silica sol showed no antifungal effect. Pine and beech wood impregnated with cationic silica sol exhibited significantly reduced mass loss, effectively resisting fungal decay. Mastouri et al. (2025) impregnated birch wood with MTMS and MPTMS, and subjected untreated and treated wood samples to biological durability tests against white-rot and brown-rot fungi. The mass loss of untreated wood exposed to white-rot and brown-rot fungi was 39% and 33%, respectively, while that of treated wood decreased remarkably. The mass loss of MTMS-modified wood was below 15%, and for MPTMS-modified wood below 5%. The improved decay resistance of silicified wood is generally attributed to changes in the chemical properties of wood caused by modifiers, which may be toxic to fungal growth. Meanwhile, the fillers occupy wood pores, hindering the penetration and spread of fungal hyphae inside wood, reducing wood moisture content, and thus failing to provide sufficient water for fungi to secrete degrading enzymes.

Hydrophobic property

Owing to its natural porous structure and hydrophilic groups, wood easily absorbs moisture and water, resulting in swelling, deformation, mould, and weakened mechanical properties (Li et al. 2026). Hydrophobic modification forms a hydrophobic barrier in or on wood, effectively blocking water penetration, thus enhancing dimensional stability, durability, and biological resistance, and prolonging its service life (Ding et al. 2022, Xia et al. 2020, Jian et al. 2024, Ding et al. 2022, Kamperidou et al. 2022, Ou et al. 2021, Yue et al. 2021). Lu prepared SiO_2 films on wood surfaces via the sol-gel method using TEOS and MTES. It was found that the contact angle increased with impregnation time. The contact angles of radial and tangential sections increased from 84° to 125° and from 68° to 125°, respectively (Lu et al. 2014). Wang et al. (2019) generated SiO_2 on wood surfaces using TEOS and graft-polymerized flexible low-molecular-weight PDMS chains to form a hydrophobic PDMS coating with a contact angle of 91.9°. After immersion in water for 19 days, the contact angle remained around 90°, showing more durable and stable hydrophobicity compared with traditional fluorinated silica coatings.

CONCLUSIONS

Although silicification modification can greatly improve wood properties, it still has limitations such as easy modifier leaching and high drying energy consumption. Accordingly, future development suggestions are proposed: develop low-cost, highly reactive precursors and multifunctional silane coupling agents to strengthen interfacial bonding with wood; explore rapid atmospheric-pressure and low-temperature curing technologies such as microwave and ultraviolet irradiation to reduce energy consumption; and combine in-situ characterization and computer simulation to clarify the interfacial bonding and reaction mechanism at the atomic/molecular level and establish an accurate structure-activity relationship.

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HONGWEI FAN[1,2], MIN LI[2], XINWEI TU[1,2], LIN YANG[1*]
[1]NAN JING FORESTRY UNIVERSITY
JIANGSU CO-INNOVATION CENTER OF EFFICIENT PROCESSING AND
UTILIZATION OF FOREST RESOURCES, NANJING FORESTRY UNIVERSITY,
NANJING 210037
PR CHINA
[2]CHINESE ACADEMY OF TROPICAL AGRICULTURAL SCIENCES
RUBBER RESEARCH INSTITUTE
HAIKOU 571101
CHINA
*Corresponding author: yanglin@njfu.edu.cn