Natural dye extracted from Dalbergia cochinchinensis residue with water fastness, mildew resistance and permeability properties for wood staining

Tao Zhu1,2 · Kai Ren1 · Jiale Sheng1 · Qiulong Zhang2 · Jian Li1,3 · Jinguo Lin1

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Abstract
Natural dyes (ND) are gaining increasing interest due to their outstanding merits of being eco-friendly, biodegradable and non-toxic. Wood dyed with extracts from Dalbergia cochinchinensis residues as ND exhibited desirable color appearance and anti-UV property, while the other potential properties of ND dyed wood in terms of water fastness, mildew resistance along with the penetrability of the ND on wood blocks dyeing have not yet been exploited. The present study was aimed at exploring these aspects for multifunction assessment of the ND dyed wood. The results showed that the total color difference ($\Delta E^*$: 4.58) and color intensity reduction (PR: 14.01%) of the ND dyed wood declined slightly after washing fastness test in comparison with that of acid red ($\Delta E^*$: 32.82; RP: 76.14%) and reactive red ($\Delta E^*$: 26.85; RP: 66.52%) dyed wood, which is indicative of its preferable water fastness, which can be ascribed to the hydrophobicity improvement of the wood surface after ND dyeing. In addition, the ND ameliorated the mildew resistance against Aspergillus niger and Trichoderma viride infection. Interestingly, the wood blocks can be completely impregnated with ND under atmospheric pressure dyeing process without any pretreatment and auxiliary. This study provided a promising approach for multifunctional ND dyed wood preparation.

Abbreviations
AGR Acid red

Jian Li
nefulijian@163.com

Jinguo Lin
linjinguo67@163.com

1 College of Material Engineering, Fujian Agriculture and Forestry University, Fuzhou 350002, Fujian, China
2 Furniture Products Quality Testing Center of Putian, Xianyou 351256, Fujian, China
3 College of Material Science and Engineering, Northeast Forestry University, Harbin 150040, Heilongjiang, China
Introduction

Available natural dye (ND) primarily derives from the crude extracts of various plants, insects, shellfish and even from lichens at ancient period. The substance with ample chromophores can be used as colorants for various substrates dyeing (Kumar and Sinha 2004; Rosenberg 2008). The aqueous extracts mainly contain flavonoids, tannins, polyphenols, etc. (Hossain et al. 2021; Kovačević et al. 2021; Nguyen and Bechtold 2021). Some of the ND exhibit considerable anti-allergic, antibacterial, and UV resistance properties toward textile dyeing (Gorjanc et al. 2016; Hong et al. 2012; Rehman et al. 2018).

ND exploitation garners increasing attention ascribed to its appreciable merits including being eco-friendly, non-hazardous, biodegradable, and compatible with the environment, etc. (Haji and Naebe 2020). The ND have been applied to materials dyeing for more than 4000 years since the ancient time (Canevari et al. 2016). Until now, researchers have principally focused their interests on the usage of extracts from different plants as ND due to the variety of chromophores in the extracts, which can endow the dyed materials with different color shades by reflecting and absorbing the visible lights (Falkehag et al. 1966; Amutha et al. 2020; Zhou et al. 2020). It has been reported that several auxiliary means involved in microwave irradiation, ultrasonic and plasma treatment can pronouncedly improve the dyeability and color strength of textile materials (Adeel et al. 2019, 2021a; Haji et al. 2021). Moreover, bio-mordant application can further reinforce this effect in the textile dyeing process (Adeel et al. 2021b; Habib et al. 2021). Interestingly, several NDs imparted the dyed textile with multi-functional properties including appealing anti-UV and antibacterial performance, which was probably due to ample natural phenols and/or flavonoid compounds existing in the extracts (Bhuiyan et al. 2017; Rather et al. 2020; Silva et al. 2018). It is worth noting that vitamin C and gallic acid are the most effective agents to ameliorate the light fastness of dyed textiles (Shahid ul and Sun 2017). Additionally, it has been reported in the literature that extracts from heartwood can be used as natural photo-stabilizers and wood preservative against termites (Brocco et al. 2019; Chang et al. 2015).
Generally, the extracts content of wood exhibits close relationship with its color appearance, and some wood of deep color invariably have higher content of phenolic components (Dellus et al. 1997; Dünisch et al. 2009). Accordingly, its biological resistance is ameliorated pronouncedly compared with sapwood, and it is undoubtedly favored by more consumers in the wooden products market. One should be aware that the rareness of this kind of wood cannot meet the extensive demands of wooden products in peoples’ daily life. Thereby fast-grown poplar wood (Populus spp.) has been chosen as potential candidate for furniture production and indoor decoration. It is notable that the poor color appearance of this kind of wood largely limits its utilization. Up to now, the dyeing treatment (mainly organic synthetic dye) served as an effective means to endow the fast-grown wood substrate with manifold color shades (Liu et al. 2015b, c). Nevertheless, this kind of dyed wood is always prone to terrible discoloration when subjected to solar irradiation (Liu et al. 2015a). As for this issue, in a previous study, a sustainable and eco-friendly dyeing method has been exploited and the issue has been solved successfully by employing *D. cochinchinensis* extracts as ND to impart the poplar veneers with even color appearance (yellowish-brown) and appreciable anti-UV property (Zhu et al. 2021). Unquestionably, this treatment strategy can improve the value-added of poplar wood by overcoming some of its inherent demerits. However, the water fastness and mildew resistance properties of this ND dyed wood are still unknown and further studies are needed for these aspects. In addition, in-depth wood block dyeing under atmospheric pressure is extremely tough due to the wood’s pronounced hierarchical anisotropy at multiple length scales (Chen et al. 2020; Ling et al. 2018; Zhu et al. 2016). An attempt was also made to explore this issue by employing ND to dye wood blocks under atmospheric pressure.

*Dalbergia cochinchinensis* belongs to the family of Leguminosae and is mainly cultivated in Thailand, Laos, Cambodia, etc. There are abundant flavonoids and phenolic compounds in the extracts from *D. cochinchinensis* and some of them have been identified and are shown in Fig. 1 (Zhu et al. 2021). The literature has revealed that the flavonoids and phenolic compounds in the wood extracts were determinant for the wood durability (Tascioglu et al. 2013; Windeisen et al. 2002). It has been validated that some wood extracts can improve the mildew resistance property of fast-grown wood (Laks et al. 1988; Salem et al. 2014). Poplar wood veneers are vulnerable to mold on account of its lower density and durability, which may lessen its service time. However, its mildew resistance property may be improved during the dyeing process due to ample flavonoids and phenolic compounds existing in the ND. Normally, dyed wood is also prone to discoloration when putting in water directly or placing in humid environment (Wang et al. 2018a). Thereby, evaluation of water resistance and mildew resistance properties of the ND dyed wood is quite necessary, which can further validate the multifunctional property of the ND dyed wood.

In continuation of a previous study (Zhu et al. 2021), this paper was mainly focused on the evaluation of the water fastness property of the ND dyed wood in comparison to that of wood dyed with chemical dyes. Moreover, the mildew resistance of ND dyed wood and the ND used for wood block staining was also investigated. This study may open new insights into multifunctional ND dyed wood preparation along with increasing the added-value of the poplar wood.
Materials and methods

Materials

Rotary-cut sapwood samples of *Poplar tomentosa* with no visual flaws including crack, knot and discoloration, collected in Fujian province, were prepared in two dimensions, i.e. 25 mm × 1.2 mm × 60 mm and 25 mm × 6.0 mm × 60 mm (Tangential × Radial × Longitudinal) and air-dried to make their moisture content less than 8%. The *D. cochinchinensis* residue was cleaned and air-dried in atmospheric environment. Afterward, it was ground into wood powder and 40–60 mesh was chosen for ND preparation. The chemical dyes (acid red GR: C_{22}H_{14}N_{4}Na_{2}O_{7}S_{2} and reactive red 3G: C_{52}H_{34}Cl_{4}N_{14}Na_{7}O_{10}S_{2}) were purchased from the Jia Ying Chemical Company, in Shanghai, China, and *Aspergillus niger* and *Trichoderma viride* were supplied by the Chinese Academy of Forestry Sciences in Beijing.

ND preparation

*D. cochinchinensis* powder was extracted with anhydrous ethanol (AE) using a Soxhlet apparatus in a thermostatic water bath at a temperature of 79 °C (boiling point of AE), and the organic extractive solution was employed to dye the samples directly (Fig. 2).

![Fig. 1 Structures of some of the main phenols and flavonoid components identified in the ND](image)
Dyed wood preparation

ND dyed wood preparation

The ND dyed wood (both the veneers and blocks) can be obtained by employing extracts from *D. cochinchinensis* as ND under atmospheric pressure along with the dip-dyeing method reported in a previous study (Liu et al. 2015c). The optimized experimental parameters including dyeing time, dyeing temperature, and dyeing concentration were set as 6 h, 79 °C and 15 g/250 mL (\(m_{\text{wood powder}}: V_{\text{AE}}\)) reported in a previous work, respectively (Zhu et al. 2021). The preparation process of ND dyed wood is summarized in Fig. 3.

AGR and R3G dyed wood preparation

Based on the reported literature (Hu et al. 2016; Liu et al. 2015b), the AGR and R3G dyed wood samples can be obtained by keeping the dye temperature at 80 °C for 4 h and setting the bath ratio as 1:20 with a dye concentration of 0.5% (w/v). The mordant 0.5% (w/v) Na\(_2\)SO\(_4\) was added to the water-soluble dye solution at the

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**Fig. 2** *D. cochinchinensis* residues and ND dye extracted with anhydrous ethanol agent at 79 °C

**Fig. 3** Schematic diagram of the preparation of ND dyed wood and multifunctional properties evaluation
initial (for AGR dyed wood) and ultimate stage of the test (for R3G dyed wood), and the pH value was adjusted to 4–5 by the 10% \( \text{H}_2\text{SO}_4 \).

**Water fastness test of ND dyed wood**

Since no standards are available for testing the water fastness of the dyed wood and the widespread application of AGR and R3G (Hu et al. 2016; Liu et al. 2015b; Wang et al. 2018b), the water fastness property of ND dyed wood in the present study was evaluated by comparing the total color difference and reflectance curves with those of AGR and R3G dyed wood after immersion in hot water (80 °C) for 3 h.

**Mildew resistance test of ND dyed wood**

The mildew resistance property of ND dyed wood was evaluated according to Chinese standard GB/T 18,261–2013 (China National Standardization Management Committee 2013). The mold control effectiveness (MCE) was calculated based on Table 1 and Eq. (1).

\[
\text{MCE} = \left(1 - \frac{D_1}{D_0}\right) \times 100\%
\]  

(1)

where \(D_1\) represents average infection value (AIV) of the treated samples and \(D_0\) is the AIV of untreated samples after 30-day mildew infection treatment.

**Permeability test of ND**

The dyed wood block was split along the longitudinal direction, and the minimum ND immersion depth was recorded (Fig. 4). The dyeing penetration rate (DPR) was calculated according to Eq. (2).

\[
\text{DPR} = \frac{L_1 + L_2}{L}
\]

(2)

where \(L\) is the total length of the sample, and the \(L_1, L_2\) the minimum ND immersion depth from the ends of the sample.

| AIV | Surface infection area                      |
|-----|--------------------------------------------|
| 0   | No hypha and mildew                        |
| 1   | Infection area less than 25%               |
| 2   | Infection area between 25 and 50%          |
| 3   | Infection area between 50 and 75%          |
| 4   | Infection area more than 75%               |

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**Table 1** Grade of surface infection value

| AIV | Surface infection area                      |
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| 0   | No hypha and mildew                        |
| 1   | Infection area less than 25%               |
| 2   | Infection area between 25 and 50%          |
| 3   | Infection area between 50 and 75%          |
| 4   | Infection area more than 75%               |
Color assessment

The colorimetric parameters of the samples including $L^*$, $a^*$ and $b^*$ were determined by X-Rite colorimetric analysis (color I7, America) with D65 standard illuminant and 10° standard observer. The total color difference $\Delta E^*$ of dyed wood after water fastness treatment was calculated from Eq. (3).

$$
\Delta E^* = \left[ (\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2 \right]^{1/2}
$$

(3)

where $\Delta L^*$, $\Delta a^*$ and $\Delta b^*$ represent the change of dyed wood before and after water fastness test in colorimetric parameters ranging from white (100) to black (0), redness (+)/greenness (−) and yellowness (+)/blueness (−), respectively.

The total color difference of the dyed samples before and after washing treatment can be classified based on visual perception levels (Table 2).

Kubelka–Munk equation (Eq. (4)) was employed to calculate the color strength ($K/S$) of the dyed wood with the wavelength ranging from 360–750 nm.

$$
\frac{K}{S} = \frac{(1 - R)^2}{2R}
$$

(4)

where $R$, $K$ and $S$ are the diffuse reflectance, the absorption and scattering coefficient, respectively.

| $\Delta E^*$ | Classification         |
|--------------|------------------------|
| 0–0.5        | Negligible             |
| 0.5–1.5      | Slightly perceivable   |
| 1.5–3.0      | Perceptible            |
| 3.0–6.0      | Appreciable            |
| 6.0–12.0     | Very appreciable       |
| > 12.0       | Beyond very appreciable|

Table 2 Relationship between total color difference and people visual sensation. Source: Adapted from Duan (2002)
The color intensity ($I$) of dyed wood before and after the washing treatment was recorded by Eq. (5), as described by Štěpánková et al. (2011).

$$I = \sum_{\lambda=380\text{nm}}^{750\text{nm}} \frac{K(\lambda) \cdot \Delta \lambda}{S} \quad \Delta \lambda = 10\text{nm} \quad (5)$$

The reduction percentage (RP) of the intensity in terms of the dyed wood was calculated by Eq. (6).

$$RP = \frac{I_b - I_a}{I_b} \quad (6)$$

where $I_b$ and $I_a$ represent the intensity of dyed wood before and after the washing treatment, respectively.

**Materials characterization**

The micromorphology of ND dyed wood before and after mildew infection treatment was observed with scanning electron microscopy (SEM, Nova Nano230, America). The contact angle of untreated samples, AE treated samples and ND dyed wood was recorded with contact angle meter (DSA-30, Germany). The contact angle of different samples was recorded per 80 ms interval time within 10 s and 60 s.

**Results and discussion**

**Evaluation of water fastness property of the ND dyed wood**

**Color parameter changes of the dyed wood after washing**

The negligible color change of undyed wood before and after washing indicated that the wood substrate exhibited a stable color property for hot water treatment (Fig. 5). In addition, slighter color fading of ND dyed wood in comparison with ARG and R3G dyed wood after water-washing treatment was perceived by the naked eye (Fig. 5). As shown in Fig. 6b, the $\Delta E^*$ of ND dyed wood was only 4.58 mainly resulting from a slight decrease in parameter $b^*$ after water washing, which was far less than that of AGR dyed wood (Fig. 6a; $\Delta E^*$:32.82) and R3G dyed wood (Fig. 6c; $\Delta E^*$:26.85). Correspondingly, the classification of surface color change based on the data classification listed in Table 2 was graded as appreciable, while the top grade was achieved for AGR and R3G dyed wood. Consequently, the water fastness property of ND dyed wood was preferable compared to that of AGR and R3G dyed wood. This was probably due to the ample phenols and flavonoid compounds existing in the ND (Zhu et al. 2021), which were hard to dissolve in the water. Moreover, distribution form difference of dyes on wood tissues may also account for this phenomenon. As reported in a previous study (Zhu et al. 2018), the ND formed a film that anchored on the wood tissues leading to greater coverage area, which was quite
Fig. 5  Photographic comparison of different wood samples before and after washing

Fig. 6  Color parameters and $\Delta E^*$ change of different dyed samples before and after being washed
different from acid and reactive dye with spots distribution form (Liu et al. 2015b; Wang et al. 2018b). Additionally, the AGR and R3G are more prone to water dissolution problems and further result in poor water fastness property.

**Surface reflectance and K/S change of the dyed wood**

Normally, a greater $R$ value signifies reduction in visible light absorbing by dyed wood resulting in pale color-shade. As shown in Fig. 7a, e, both the $R$ value of AGR and R3G dyed wood after washing increased pronouncedly compared with that of unwashed samples, which indicated that terrible color fading of AGR and R3G dyed

![Fig. 7 Reflectance and K/S spectra of differently dyed samples before and after washing](image-url)
wood occurred. However, the $R$ curves of ND dyed wood before and after washing nearly overlapped manifesting only marginal color fading occurrence (Fig. 7c).

Based on the Kubelka–Munk theory, there is a linear relation between $K/S$ value and chromophores variation in the range of visual light spectra (Chen et al. 2012; Huang et al. 2012). $K/S$ spectra variation reveals the surface color change of dyed wood before and after washing. As shown in Fig. 7b, f, the $K/S$ curves of both the AGR and R3G dyed wood declined apparently in comparison with the unwashed samples. Nevertheless, only slighter $K/S$ spectra changes retained for the ND dyed wood (Fig. 7d). Moreover, the ND dyed wood in terms of the RP for the $I$ value was far lower (14.0%) than that of AGR (76.14%) and R3G dyed wood (66.52%), as data revealed in Table 3. All the aforementioned results further elucidated the water fastness of ND dyed wood was preferable.

Hydrophobicity evaluation of ND dyed wood

The contact angles (CA) of different test samples were measured to evaluate the hydrophobicity of ND dyed wood. As shown in Fig. 8a, b, the CA variation of the AE treated wood was negligible after 10 s compared with that of undyed wood, which indicated that AE treatment had no effect on the hydrophobicity of substrates. Interestingly, the CA of ND dyed wood after 10 s (Fig. 8c) and even more than 60 s (Fig. 8d) was still apparently greater than that of undyed and AE treated wood. It can be deduced that ND can be the determinant for ameliorating the hydrophobicity of wood, which was probably due to the ND film generated and anchored on the wood fibers (Zhu et al. 2021). Furthermore, the main phenols and flavonoid components in the ND may be poorly soluble in water, which can prominently ameliorate the water fastness of ND dyed wood.

Moreover, the dynamic change curves of different samples are revealed in Fig. 8e. It can be clearly seen that the CA of the ND dyed wood was stable in the whole test process, while a sharp decline in the CA occurred in both the undyed and AE treated wood. All the analyses demonstrate the ND can prominently improve the hydrophobicity of wood, which can account for the water fastness property improvement of the ND wood.

Up to now, wood dyeing was prevailingly conducted in aqueous solution with chemical synthetic dyes including AGR and R3G (Hu et al. 2016; Liu et al. 2015a and 2015b). Consequently, the chemical dyes will readily dissolve in the water again and lead to poor washing fastness when subjected to hot water treatment (Wang et al. 2018a). The current study can solve this issue due to the ample phenolics and

### Table 3

| Sample       | $I_b$          | $I_a$         | RP        |
|--------------|----------------|--------------|-----------|
| AGR dyed wood| $1627.74 \pm 38.71^*$ | $388.36 \pm 12.82$ | 76.14%    |
| G3R dyed wood| $1059.18 \pm 24.99$  | $354.59 \pm 11.52$  | 66.52%    |
| ND dyed wood | $1094.27 \pm 24.55$  | $941.01 \pm 18.51$  | 14.01%    |

*Represents the standard deviation
flavonoids existing in ND, and these components may be hard to dissolve in water. Undoubtedly, water fastness improvement of the ND dyed wood can maintain the color appearance steadily and partly prolong its service time.

**Mildew resistance of the ND dyed wood**

Sapwood is invariably prone to suffer organism erosion under favorable environments leading to partial damage of the wood surface (Rodrigues et al. 2012; Schultz et al. 2007; Schwarze 2007). *Aspergillus niger* and *T. viride* growth and distribution on different test samples after 30 days are shown in Fig. 9. It was evident that both the undyed and AE treated wood had no inhibiting effect against both *A. niger* and *T. viride* indicating that there is no improvement in the anti-mold property of wood after AE treatment. However, the ND dyed wood still exhibited certain inhibition behavior against the two molds even after 30 days. Consequently, it can be inferred that the ND can impart the dyed wood with superior mold inhibition property.

Based on Table 1, the AIV curves of different test samples are shown in Fig. 10a, b. The AIV of the ND dyed wood against the two molds increased with increasing time but was remarkably lower than that of control and AE treated wood. This showed that the ND dyed wood exhibited preferable anti-molds property even after 30 days. According to Eq. (1), the MCE of AE treated and ND

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**Fig. 8** Photograph of the surface contact angle of water on a undyed wood after 10 s, b AE treated wood after 10 s, c ND dyed wood after 10 s, and d ND dyed wood after 60 s; e surface contact angle change of water on different samples.
Fig. 9  Photographs of different test samples against *A. niger* and *T. viride* infection for 30 days

Fig. 10  Trends of AIV of different test samples against *T. viride* (a) and *A. niger* (b); MCE of ND dyed wood against *T. viride* (c) and *A. niger* (d)
dyed wood was calculated and is shown in Fig. 10c, d. It can be seen that MCE of ND dyed wood was improved against the two molds after the dyeing process, and the inhibition effect of ND dyed wood against *T. viride* (54.25%) was superior to that of *A. niger* (27.00%) due to its greater infection effect.

The micrographs of molds distribution on wood tissues were observed to investigate the mildew resistance property of ND dyed wood. As shown in Fig. 11a, the vessel wall of undyed wood was smooth and mildew was absent. However, numerous molds were present on undyed wood tissues after anti-mold assay (Fig. 11b), which revealed that poplar wood was extremely vulnerable to mold infection. Noticeably, drastic reduction in mold distribution occurred on the tissues of ND dyed wood (Fig. 11e, f). This was indicative of the considerable anti-molds property of ND dyed wood, which is ascribed to ND film generation and anchoring on the poplar wood (Fig. 11d). As reported in several studies, the phenolic and flavonoid compounds can break the cytoderm and cytomembrane of the molds leading to protein damage and further exhibit appreciable mildew resistance property (Jin 2019; Kasiri and Safapour 2014; Silva et al. 2018; Talaro 2016; Tascioglu et al. 2013). Consequently, the ample phenols and flavonoids present in ND may account for the mildew resistance amelioration of the ND dyed wood. However, the process of ND against mildew is considerably complicated and more studies are needed to fill this gap in the future.

![Fig. 11 SEM micrographs of undyed wood a, undyed wood against *T. viride* b and *A. niger* c, ND dyed wood before anti-molds test d, ND dyed wood against *T. viride* e and *A. niger* f. Note: the mildew infection assay of all the different test samples was carried out for 30 days](image-url)
The permeability of ND was evaluated by comparison of the DPR value with that of AGR and R3G. As shown in Fig. 12c, the wood blocks were completely impregnated with ND, whereas the penetrability of AGR and R3G was quite poor along the radial direction (Fig. 12a, b). The DPR of ND dyed wood (100%) was far greater than that of AGR (3.33%) and R3G dyed wood (3.03%), which indicated that the permeability of the ND was superior (Fig. 12d). Migration and permeation of the dye molecules were the key factors to determine the penetrability of the wood dyeing (Duan 2002). Additionally, the molecular weight of the dye and the physicochemical property of the dye liquor were also pivotal for wood dyeing in depth (Bao and Hu 1990). In the current study, no pretreatment was conducted on wood blocks before dyeing and the molecular weight of the components in ND with exception of rutin was much lower than that of AGR and R3G (Table 4). The dyes with lower molecular weight would be prone to immerse the wood internal substrate by traversing various channels including pore, pits, intercellular space, etc. This may be the reason for the preferable penetrability of ND on wood blocks. In addition, another tentative explanation is that higher polarity resemblance between the dye liquor and wood substrate can provoke the amelioration of the dye molecular movement and further lead to considerable penetrability of the dye (Deng et al. 2006; Wizi et al. 2018). Unquestionably, the AE as an organic dye solution may have higher polarity.
resemblance to wood substrates than the aqueous solution used in the AGR and R3G dye process, and resulted in greater penetrability of the ND.

Up to now, various means including chemical soaking (NaOH or H₂O₂ solution), microwave assistance or vacuum pretreatment, etc. on raw wood was indispensable for in-depth wood block dyeing using chemical dyes (Cao et al. 2008; Chang et al. 2009; Deng et al. 2006; Hu et al. 2015). Accordingly, the related experimental cost and period will be partially increased and prolonged. Moreover, it is notable that some pretreatment methods may lead to internal wood damage and further shorten the service time of dyed wood (Zhang et al. 2011). Interestingly, the wood blocks were saturated with the ND without any pretreatment in the present study which is indicative of unexpected penetrability of the ND. The considerable penetrability of ND may provide a novel insight into wood blocks dyeing. However, the movement of dyes in the wood substrate was quite complicated, and more studies are still needed to fill the knowledge gaps in this area.

### Conclusion

In the present study, the water fastness and mold inhibition properties of ND dyed wood were evaluated. The ΔE* and I of ND dyed wood declined lesser after washing treatment in comparison to AGR and R3G dyed wood, indicating the water fastness of ND dyed wood was quite appreciable. This may be attributed to the surface hydrophobicity of ND dyed wood improved prominently and ND film generation and depositing on the surface of wood. Concurrently, the ND dyed wood exhibited mildew inhibition property against *T. viride* and *A. niger* due to the abundant phenols and flavonoid in the ND conferring mildew resistance to poplar wood veneers. Additionally, the wood blocks can be completely impregnated with ND using AE extracts as dye solution under atmospheric pressure. Unquestionably, it gives evidence that this dyeing scenario can achieve tremendous penetrability for wood block staining.

The multifunctional property of ND dyed wood has been validated in terms of preferable water fastness, mold growth inhibition in conjunction with unexpected penetrability behavior of the ND without any mordant addition and pretreatment.
Results of this study can provide potential novel insight into multifunctional dyed wood preparation and guarantee extended service time of the ND dyed wood for possible outdoor usage.

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Declarations

Conflict of interest The authors report no declarations of interest.

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