Evaluation of the Association between Natural Mold Resistance and Chemical Components of Nine Wood Species

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The association between natural mold resistance and the wood's chemical components was studied for nine wood species. The mold resistance of the different wood species was tested by artificially accelerated tests and scanning electron microscopy (SEM). The chemical components were analyzed by gas chromatography-mass spectrometry (GC-MS). The results indicated that the sequence of mold resistance of different wood flours was as follows, from greatest to least resistance: spruce, Mongolian pine and camphor, toon and teak, eucalyptus (*E. urophylla* and *E. grandis* × *E. urophylla*), sweetgum, and castor straw fiber. GC-MS analysis indicated that the total contents of the antifungal compounds present in all wood flour extractives were consistent with the sequence of mold resistance of wood flour. This suggested that the natural durability of wood flour against molds was affected by its chemical components.

Keywords: Mold; Mold resistance; Wood flour; Chemical components

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INTRODUCTION

Wood and wood products mainly consist of cellulose, hemicellulose, lignin, and extractives. They have been widely applied in buildings, furniture, and paper pulp production due to their advantages, such as high strength-weight ratio, impact resistance, and high processability (Li *et al*. 2015). With the continuous decline of forest resources and their increasing prices, wood fibers (or biomass fibers), which come from both forest and agricultural residues, are now increasingly being used as fillers in wood composites, such as wood-plastic composites, wood-metal composites, wood-inorganic composites, and wood-glass fiber composites.

Due to their susceptibility to weathering and hygroexpansion, wood and wood products are prone to attack from biological pathogens, such as wood-decay fungi and molds (Li *et al*. 2015; Salem *et al*. 2017). Wood-decay fungi change the chemical structure of lignin, cellulose, and hemicellulose, resulting in a substantial loss of weight and strength (Durmaza *et al*. 2016). Molds growing on wood surfaces do not degrade cellulose, lignin, and hemicellulose in wood. Hence, they do not always deteriorate its mechanical and physical properties. However, the large quantities of cellulolytic enzymes (cellulases and hemicellulases), extracellular metabolites, and pigments produced by molds cause discoloration or staining on the wood surface (Sirmah *et al*. 2009; Sohail *et al*. 2011). Under favorable conditions of high moisture content, molds cause disfigurement of wood in a

very short time, and with their strong propagation, some lead to soft rot of lignocellulosic materials (Fojutowski *et al.* 2014). Furthermore, the growth and colonization of molds on wood surfaces provide a medium for other deterioration agents such as insects and decay fungi, which disseminate into cells through cell walls, pores, and pits (Sterflinger and Piñar 2013; Salem 2016). In general, the deterioration of physical and mechanical properties of wood and wood products results from a combination of biological agents.

The resistance to fungal attack varies among wood species. Wood species are mainly composed of carbon, oxygen, hydrogen, nitrogen, and several metal ions (Salem 2016). The elemental composition changes with wood species, which significantly influences its fungal susceptibility. Sugars and starches present in wood provide a suitable environment for growth and reproduction of fungi, which alter the properties of wood and wood products (Mansour and Salem 2015; Salem 2016). There are different types and contents of chemical components in various wood species (Xu *et al.* 2015). Some wood species contain highly toxic chemical substances, such as tannins, fatty acids, aldehydes, and ketones, which result in a passive or negative effect on the susceptibility and resistance of wood against fungi (Jeloková and Šindler 2001; Liu *et al.* 2008).

There is little information regarding the effects of chemical components of different wood species on the susceptibility of mold growth on wood flour. Thus, the aim of this work was to evaluate the associations between the natural mold resistance and the chemical components of wood flour species. Wood flours from spruce, Mongolian pine, castor straw fiber, camphor, toon, teak, sweetgum, and two eucalyptus species (*Eucalyptus urophylla* and *E. grandis* × *E. urophylla*) were examined. The natural mold resistances of various wood species were examined and estimated using artificially accelerated tests. Meanwhile, surface and fracture morphology of wood specimens were observed by scanning electron microscopy (SEM). The components of wood flour species were extracted *via* Soxhlet apparatus and analyzed by gas chromatography-mass spectrometry (GC-MS).

EXPERIMENTAL

Materials

Wood flour from nine different species, including spruce (*Picea asperata*), Mongolian pine (*Pinus sylvestris* var. *mongolica*), castor straw fibers (*Ricinus communis*), camphor (*Cinnamomum camphora*), toon (*Toona ciliate*), teak (*Tectona grandis*), sweetgum (*Liquidambar formosana*), and two eucalyptus species (*Eucalyptus urophylla* and *E. grandis* × *E. urophylla*), were obtained from a commercial factory. Before being used, the wood flours were ground and sieved with sizes of 20 mesh to 100 mesh, and then dried to a constant weight at 105 °C.

Five mold specimens, including *Aspergillus niger* (GIM 3.5487), *Trichoderma viride* (GIM 3.139), *Penicillium funiculosum* (GIM 3.103), *Aureobasidium pullulans* (GIM 3.44), and *Chaetomium globosum* (CGMCC 3.3601), were supplied by the Microbial Culture Collection Center of the Guangdong Institute of Microbiology, Guangzhou, China.

Methods

Accelerated mold resistance test

The mold resistance of wood flour species was tested using an artificially accelerated method. First, *A. niger*, *T. viride*, *P. funiculosum*, *A. pullulans*, and *C. globosum* were grown separately and maintained in Petri plates on potato dextrose agar (PDA)

medium (containing 200 g/L of potato extract, 20 g/L of glucose, and 20 g/L of agar) at 28 ± 2 °C and 85% relative humidity for 10 d to 15 d, until the whole surface of the plate was sufficiently covered with fungal hyphae and mycelia. A spore suspension of each of the five test molds was prepared by washing the surface of each fungal culture with 10 to 15 mL of sterile water. The suspension was transferred to a sterile Erlenmeyer flask that contained sterile water and glass beads. The flask was vibrated vigorously to separate the spores. A precipitate was obtained after filtration and centrifugation of the spore suspension. The precipitate was then re-suspended in 100 mL of sterile water, which yielded approximately 1×10^7 spores/mL. This procedure was repeated for each mold. Equal volumes of the resultant spore suspensions were blended to obtain the final spore suspension mixture. This suspension was then transferred to a 50 mL spray bottle and used as the source of fungal inoculum for testing.

Prior to the mold resistance testing, each of the dried wood flours was mixed with sterile water at a water to wood flour ratio of 20% (v/m, mL/g). All wood flour specimens were sprayed with equal amounts of the mixed spore suspension and incubated at 28 °C ± 2 °C with 85% relative humidity for 28 d. Following incubation, the mold ratings of wood flour were rated visually according to ASTM G21 (2013) with ratings of 0 to 4, where 0 indicated no mold growth, and 4 indicated heavy mold growth (60% to complete coverage).

Scanning electron microscopy

Microbial growth on the surface of each wood flour sample before and after mold resistance test was observed using a scanning electron microscope (Hitachi S-3000N, Guangzhou, China) at an accelerating voltage of 15 kV. Each wood flour sample was dried and sputter-coated with a thin layer of gold prior to observation.

Extraction of the chemical components of wood flour

Wood flour samples were air-dried and extracted by the Soxhlet method with benzene/ethanol (absolute) (1:1, v/v) solvent. Each sample weighing 3 g was placed in a Soxhlet extractor for 8 h, at a reflux rate of not less than 6 times an hour. The obtained solutions were evaporated using a rotary evaporator and then re-dissolved in 5 mL of methanol to obtain the extractives.

Gas chromatography-mass spectrometry analysis

The chemical components of extractives were analyzed using a gas chromatograph-mass spectrometer device (7890A-5975C, Agilent Technologies, Guangzhou, China) equipped with a DB-5MS silica capillary column (30 mm × 0.25 mm × 0.25 μm, Agilent). The oven temperature was initially maintained at 80 °C for 4 min, gradually increased to 200 °C at a rate of 10 °C/min, and raised to 300 °C for 10 min. The temperature of the injector was set to 290 °C, and the detector was set to 300 °C. Highly pure helium was used as the carrier gas at a constant flow rate of 1.0 mL/min. The temperatures of the transfer line, quadrupole, and ion source were 250 °C, 150 °C, and 230 °C, respectively. Electron ionization (EI) was used as the ion source with an electronic energy of 70 eV and the mass scanning range was set from 30 amu to 500 amu in full scan. The volume of the injected sample was 1 μL with a split ratio of 30:1.

The chemical components were identified by comparing their mass spectra with those published in the National Institute of Standards and Technology database (https://www.nist.gov/). The peak areas of all the components were calculated by using Xcalibur 2.0 software (Thermo Fisher Scientific, Waltham, MA, USA), and the relative contents of chemical compounds were calculated from the ratios of the peak areas.

RESULTS AND DISCUSSION

Accelerated Mold Resistance of Wood Flour

Table 1 and Fig. 1 illustrate the growth and colonization of mold and the mold ratings of nine wood flour species after an incubation period of 28 d. There were obvious differences in the mold ratings for different wood flour species. The best mold resistance among the nine wood flour species was exhibited by the spruce wood flour. No mold growth and colonization was observed on the surface of the spruce wood flour (Fig.1A), which corresponded to the mold rating of 0 after 28 d of exposure. Excellent mold resistance was found in the wood flours of Mongolian pine, camphor, toon, and teak. These wood samples showed excellent durability against molds, which corresponded to very little mold growth and colonization on the surface, with mold rating at 28 d of level 1, as shown in Figs.1B, D, E, and F.

Among these four wood flours, Mongolian pine and camphor exhibited comparatively higher mold resistance because no mold colonies were found at 14 d, while the rest were slightly colonized. Wood flours of two eucalyptus species (*E. urophylla* and *E. grandis* × *E. urophylla)* and sweetgum showed relatively lower mold resistance. They were colonized faster (7 d) accompanied with medium coverage of mold, and the final mold ratings (at 28 d) for these three wood flours were 2 (Figs.1G, H, and I). Castor straw fiber, as shown in Fig. 1C, exhibited the lowest resistance to mold. A heavy mold growth and colonization appeared after 7 d exposure (Level 3), and the final rating at 28 d was Level 4, which was equivalent to 100% mold coverage on the surface of castor straw fiber. Thus, the sequence of durability of different wood flours against molds was as follows: spruce > Mongolian pine and camphor > toon and teak > eucalyptus (*E. urophylla* and *E. grandis* × *E. urophylla*) > sweetgum > castor straw fiber.

Table 1. Visual Mold Ratings of Wood Flour Species after Exposure to Molds

Wood Flour Species	Mold Ratings			
	0 d	7 d	14 d	28 d
Spruce	0	0	0	0
Mongolian pine	0	0	0	1
Castor fiber	0	3	4	4
Camphor	0	0	0	1
Toon	0	0	1	1
Teak	0	0	1	1
Sweetgum	0	1	2	2
E. urophylla	0	1	1	2
E. grandis × *E. urophylla*	0	1	1	2

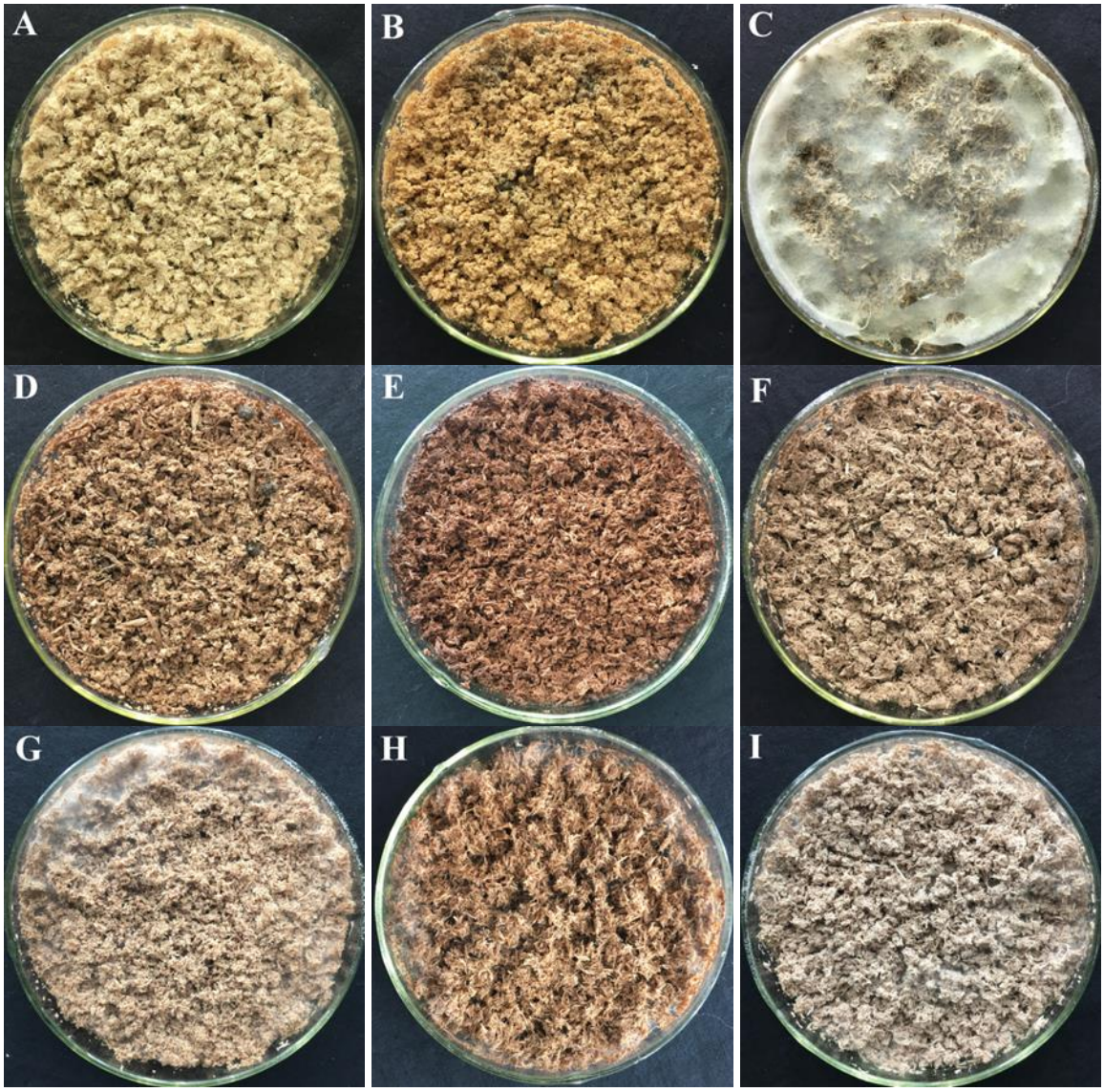


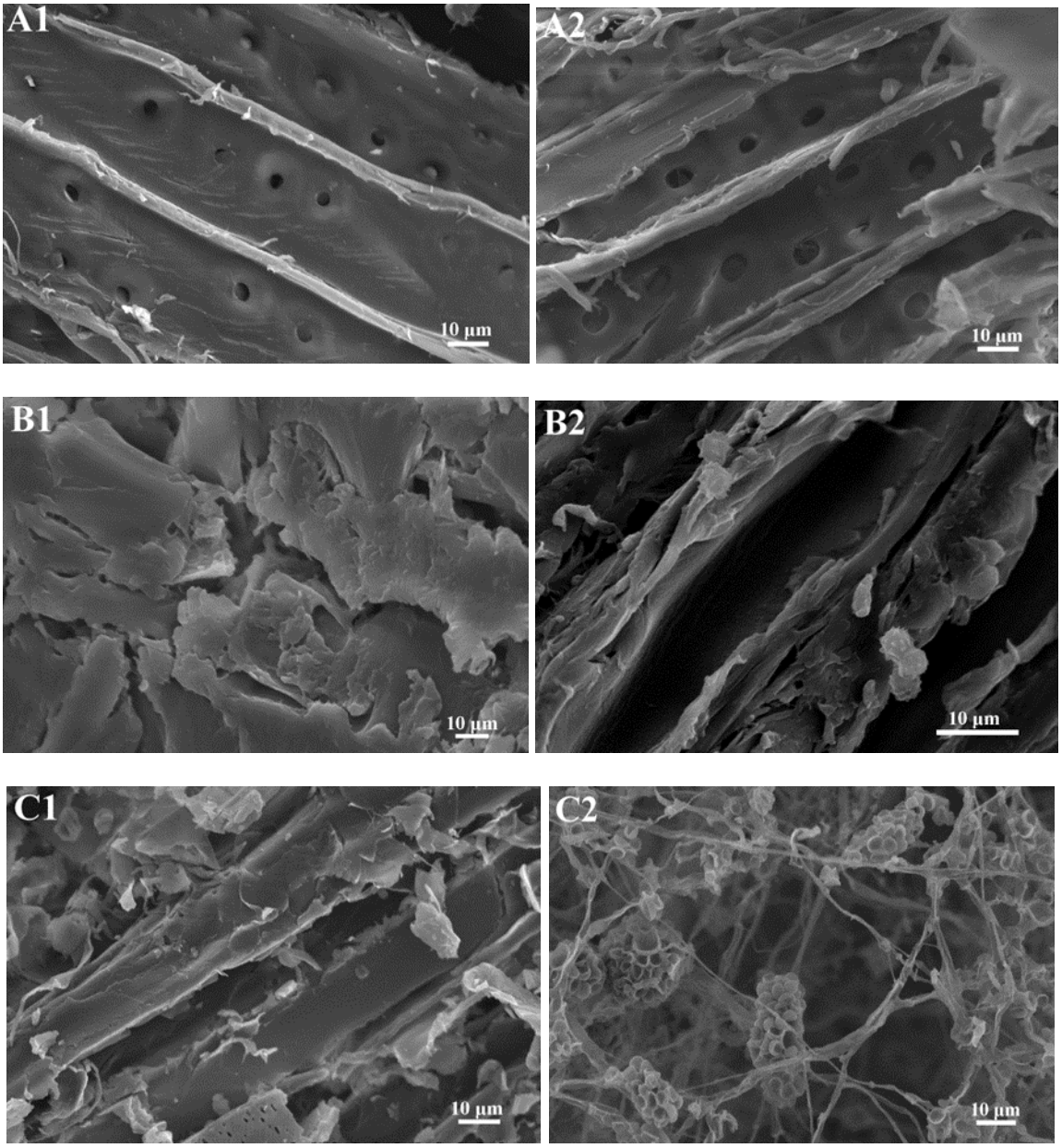
Fig. 1. Mold resistances of various wood flour species after 28 days exposure to molds: (A) spruce; (B) Mongolian pine; (C) castor fiber; (D) camphor; (E) toon; (F) teak; (G) sweetgum; (H) *E. urophylla*; (I) *E. grandis* × *E. urophylla*

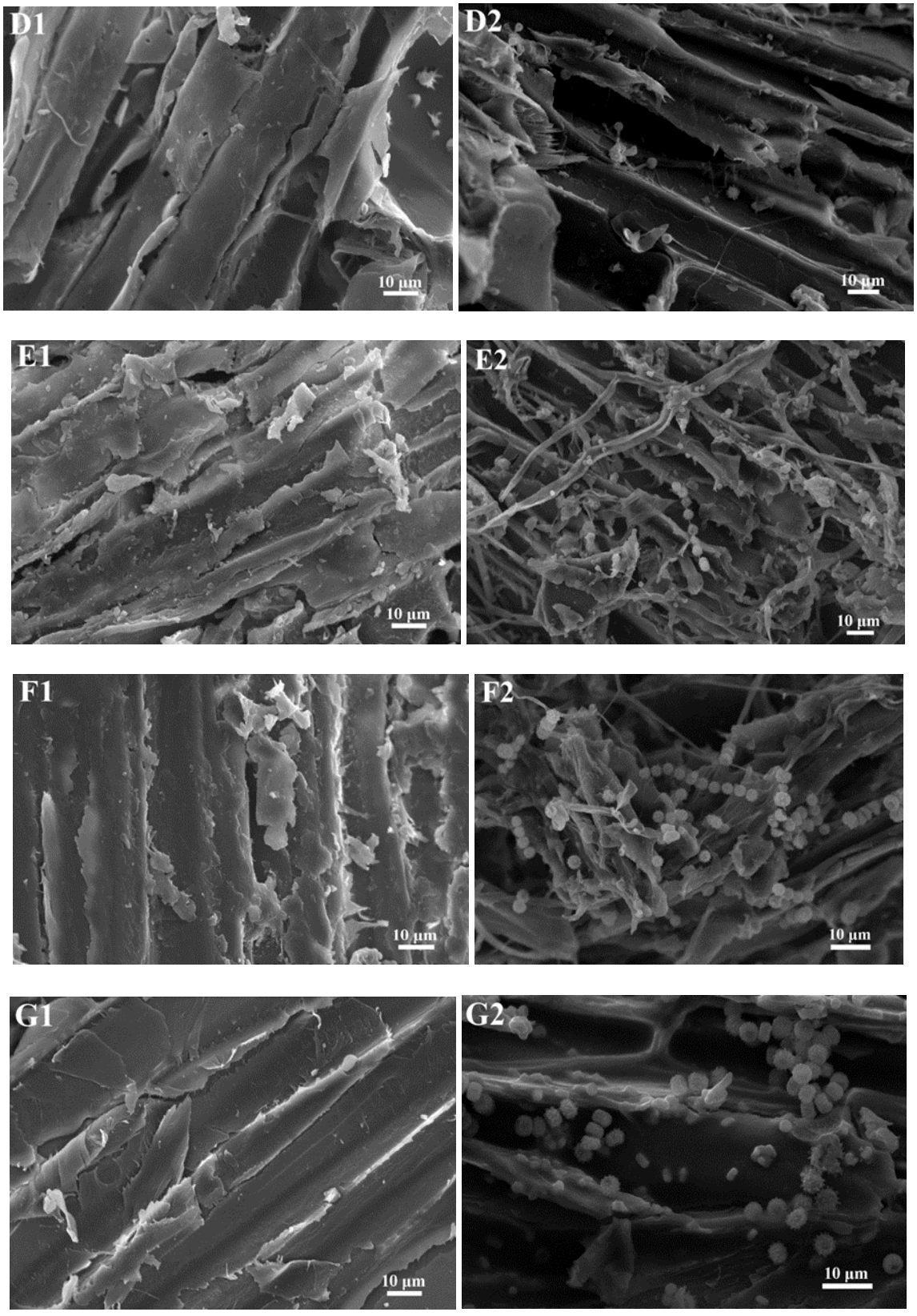
SEM Examination of Wood Flour before and after Mold Resistance Test

SEM images of various wood flour species before and after mold resistance tests are shown in Fig. 2, which directly reveal the extent of mold growth, distribution, spores, and hyphae on the wood flour samples. The wood flour before mold fungi tests were used as the control samples (Figs. 2A1-I1). As shown in Figs. 2AI-I1, no mold spores and hyphae were found on surfaces for all the control wood flour. However, big differences can be observed among the nine wood flours after 28 days treatment with molds. For spruce wood flour, there was no hyphae, and spores were found on its surface (Fig. 2A2), which corresponded the mold rating of 0. Furthermore, the surfaces of the Mongolian pine and camphor wood flour samples (Figs. 2B2 and D2) were covered with only a few spores.

A greater number of hyphae and spores were observed in the toon and teak wood flours (Figs. 2E2 and F2). These observations were consistent with the mold ratings mentioned above. Figures 2G2, H2, and I2 show a high degree of colonization and mold growth on the surfaces of sweetgum and two species of eucalyptus wood flours (*E. urophylla* and *E. grandis* × *E. urophylla*), in which the spores were occasionally produced either individually or in short chains.

In castor fiber, the mold formed a dense hyphal network and produced large fruiting structures that released large numbers of spores on the outside of castor fibers, as shown in Fig. 2c. This mold colonization strategy releases of enzymes and organic acids into the interior regions of the wood. The surface elemental composition was affected and showed different degrees of hyphal penetrations (De Boer *et al.* 2010; Mansour and Salem 2015; Mansour *et al.* 2015).

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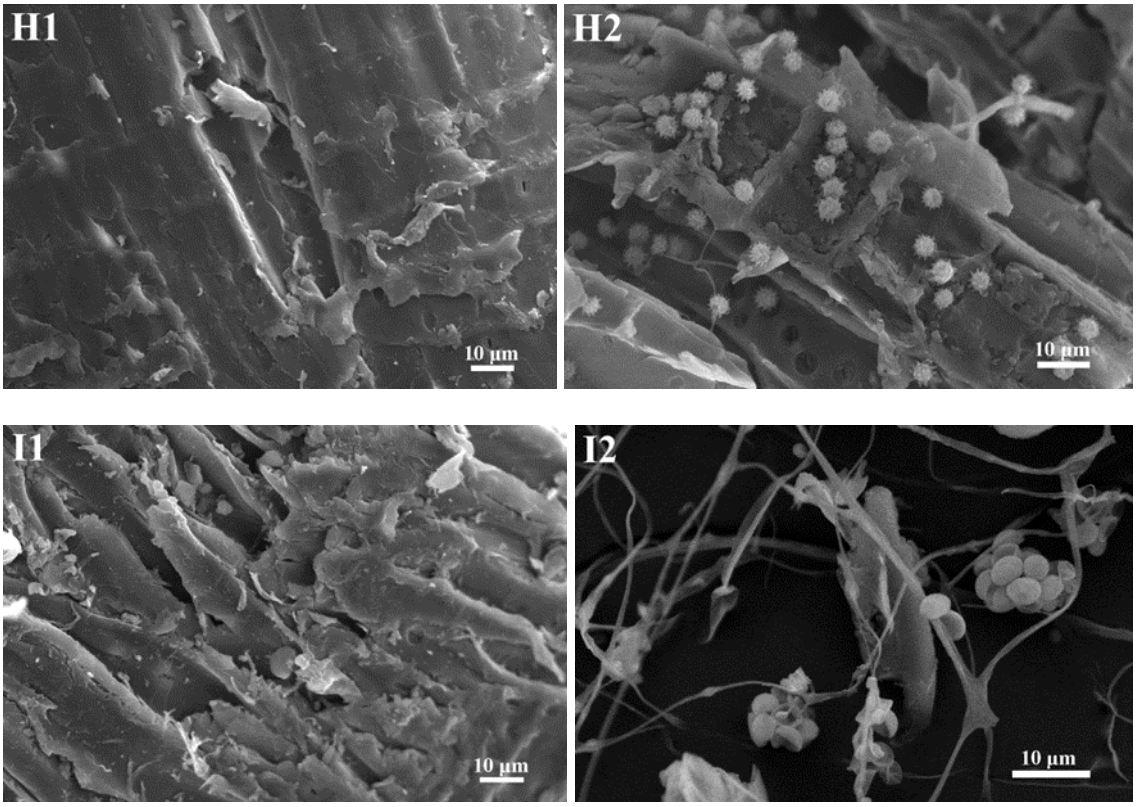

Fig. 2. SEM images of various wood flour species before (A1-I1) and after (B2-I2) mold resistance tests: (A) spruce; (B) Mongolian pine; (C) castor fiber; (D) camphor; (E) toon; (F) teak; (G) sweetgum; (H) *E. urophylla*; (I) *E. grandis* × *E. urophylla*

Chemical Components of Various Wood Flour Species

To investigate the differences in mold resistance between the nine wood flour species, extractives of each wood flour sample were analyzed by GC-MS. The chemical compounds and their relative contents are listed in Tables 3 through 11.

Seventeen compounds were identified in spruce wood flour extractives (Table 3). The major components included *β*-sitosterol (33.7%), *γ*-sitosterol (24.32%), and cedrol (15.23%). These compounds display strong antifungal activities against a wide variety of fungi, such as *Fusarium moniliforme*, *A. niger*, *Cladosporium cladosporioides*, *Phytophthora infestans*, *Penicillium notatum*, *Lenzites betulina*, *Trametes versicolor*, *Laetiporus sulphureus*, *Gloeophyllum trabeum*, *Rhizoctonia solani*, *F. solani*, *Pestalotiopsis funereal*, and *Ganoderma australe* (Lall *et al.* 2006; Cheng *et al.* 2011; Zhang *et al*. 2011; Cheng *et al.* 2012; Choi *et al.* 2017). Vanillin (2.36%), *α*-cedrene (2.63%), and *β*-cedrene (2.73%) were also likely responsible for the resistance to the mold attack. Vanillin has inhibitory properties against fungi and bacteria and has a synergistic effect to enhance the antifungal effect of plant essential oils against *Botrytis cinerea* (Rattanapitigorna *et al.* 2006; Cava-Roda *et al.* 2012). Cedrene (*α*-Cedrene and *β*-Cedrene) is a major constituent of essential oils; it displays inhibitory effects against leukemia, anaerobic bacteria, yeast, and some decay fungi (Nibret and Wink 2010; Mun and Prewitt 2011). Because spruce wood contains more than 80% content of compounds with notable antifungal activities, it has an outstanding resistance to mold growth and decay.

Table 3. Chemical Compounds and Their Relative Contents in Spruce Wood Flour

Wood Species	Chemical Component	Relative Content (%)
Spruce	Vanillin	2.36
	α-Cedrene	2.63
	β-Cedrene	2.73
	Cedrol	15.23
	Heptadecane	2.27
	Octadecane	2.51
	Labda-8(20),12,14-triene	1.31
	27-Nor-25-ketocholesterol	5.16
	Tetracosane	3.84
	β-Sitosterol	33.70
	Triacontane	3.94
	γ-Sitosterol	24.32

Table 4. Chemical Compounds and Their Relative Contents in Mongolian Pine Wood Flour

Wood Species	Chemical Component	Relative Content (%)
Mongolian pine	Benzyl alcohol	3.06
	Benzothiazole	3.09
	Vanillin	45.89
	3'-Hydroxy-4'-methoxyacetophenone	18.57
	Heptadecane	10.91
	4-Hydroxy-3-methoxycinnamaldehyde	8.84
	Octadecane	5.16
	Nonacosane	1.41
	1-Iodo-octadecane	3.07

Nine compounds were identified in Mongolian pine extractives (Table 4). Among these compounds, vanillin (45.89%) is the most abundant compound, which is used in medical applications and as a flavoring agent because of its strong activity against bacteria, yeasts, and fungi (Rattanapitigorna *et al.* 2006; Cava-Roda *et al.* 2012). Benzyl alcohol (3.06%), benzothiazole (3.09%), and 4-hydroxy-3-methoxycinnamaldehyde (8.84 %) also play an important role in fungal durability of the Mongolian pine. Benzyl alcohol exhibits significant antifungal activities towards *Colletorichum camelliae* (Zhang *et al.* 2006). Benzothiazole and its derivatives are important fragments in medicinal chemistry due to their wide range of biological activities, which include anti-tumor, anti-cancer, anti-inflammatory, anti-viral, and anti-fungal activities against *Alternaria solani* and *Botrytis cinerea* (Seenaiah *et al.* 2014; Gao *et al.* 2017). 4-Hydroxy-3-methoxycinnamaldehyde has been described as an antifungal compound due to its ability to inhibit the growth of *Fusarium verticillioides* (Carpinella *et al.* 2003). These compounds synergistically improved the fungal resistance of Mongolian pine wood.

The GC-MS of castor fiber showed twenty compounds (Table 5). The main components were palmitic acid (17.57%), octadec-9-enoic acid (14.08%), 4-ethenyl-1,4-dimethyl-3-(2-methylprop-1-enyl), and cycloheptene (10.82%). The chemical components responsible for mold resistance were palmitic acid and *γ*-sitosterol. The former is a fatty acid that is widely distributed in the extractives of plants and displays a strong inhibiting

effect on the growth of *Alternaria solani*, *Colletotrichum lagenarium*, and *Fusarium oxysporum* (Liu *et al.* 2008). The latter is an epimer of *β*-sitosterol. Both *β*-sitosterol and *γ*-sitosterol show strong antimicrobial activities against some bacteria and fungi. Although palmitic acid and *γ*-sitosterol provided some antifungal activity for castor fiber, these compounds provided poorer fungal resistance than in the other wood flour because of their lower relative content (17.57% and 2.06%, respectively).

Table 5. Chemical Compounds and Their Relative Contents in Castor Fiber Flour

Wood Species	Chemical Component	Relative Content (%)
Castor fiber	5-Hydroxy-2-decenoic acid lactone	7.89
	2-Methoxy-4-vinylphenol	3.78
	3-Hydroxy-4-methoxybenzoic acid	4.06
	3-Ethoxybenzaldehyde	3.36
	D-arabinitol	3.39
	Palmitic acid	17.57
	Ricinine	5.24
	Octadec-9-enoic acid	14.08
	Octadecanoic acid	4.86
	1-Cyclopropene-1-pentanol, α, ε, ε,2-tetramethyl-3-(1-methylethenyl)-	3.91
	4-Ethenyl-1,4-dimethyl-3-(2-methylprop-1-enyl) cycloheptene	10.82
	(1R)-7*β*-Ethenyl-1,2,3,4,4a,4bα,5,6,7,9,10,10a*α*-dodecahydro-2β-hydroxy-1,4aβ,7-trimethyl-1*α*-phenanthrenemethanol	3.77
	12-Ethylsophoramine	7.53
	9-Methoxy-4-(2-methylbut-3-en-2yl)furo[3,2-g]chromen-7-one	2.89
	γ-Sitosterol	2.06
	4,22-Stigmastadiene-3-one	1.50
	β-Sitostenone	3.29

In camphor wood extractives, the main compounds were 1-docosene (14.47%) and *γ*-sitosterol (33.87%). The following seven compounds, elemol (4.61%), cedrol (3.73%), palmitic acid (8.84%), elaidic acid (1.51%), campesterol (5.60%), stigmasterol (2.52%), and *γ*-sitosterol, were the key components that imparted camphor wood flour with fungal resistance (Table 6).

The antifungal activities of cedrol, palmitic acid, and *γ*-sitosterol have been described above. Elemol, extracted from the fresh rhizomes of *Zingiber officinale*, was reported to show a fungistatic activity against *Penicillium griseofulvum* (Philippe *et al.* 2012). Elaidic acid is an unsaturated fatty acid, which shows strong antiradical, antibacterial, anticandidal, and antifungal activities against *A. niger* and *A. flavus* (Hanene *et al.* 2015). Campesterol and stigmasterol are the most important plant sterols that are often present in lipid-rich plant foods such as olive oil, nuts, legumes, and seeds. The antifungal activities of campesterol and stigmasterol against *Phytophthora infestans* have been reported by Choi *et al.* (2017).

Table 6. Chemical Compounds and Their Relative Contents in Camphor Wood Flour

Wood Species	Chemical Component	Relative Content (%)
Camphor	3-Ethyl-5-(3-ethyl-2(3H)-benzothiazolylidene)-2-(p-tolylimino)-4-thiazolidinone	1.80
	Bornane-2,5-dione	4.43
	Elemol	4.61
	Cedrol	3.73
	1,4-Methanoazulen-9-one,decahydro-1,5,5,8a-tetramethyl-, [1R-(1α,3aβ,4α,8aβ)]-	7.69
	Palmitic acid	8.84
	Elaidic acid	1.51
	Octadecanoic acid	2.40
	9-Octadecenamide, (Z)-	1.48
	3-Eicosene,(E)-	2.20
	1-Docosene	14.47
	Campesterol	5.60
	Stigmasterol	2.52
	γ-Sitosterol	33.87
	β-Sitostenone	4.08

There were in total six compounds that affected the fungal resistance of toon wood, namely *γ*-sitosterol (23.37%), cycloeucalenol (16.97%), palmitic acid (12.14%), 3,4-dihydroxybenzoic acid (3.56%), vanillin (2.15%), and α-muurolene (2.10%) (Table 7). As mentioned above, *γ*-sitosterol, palmitic acid, and vanillin possess strong antifungal properties. Both cycloeucalenol and 3,4-dihydroxybenzoic acid exhibited antifungal activity against *A. niger*, *Candida albicans*, and *Cryptococcus neoformans* (Ocharo 2012; Amugune 2013). *α*-Muurolene displays antifungal activity against the phytopathogenic fungus *Cladosporium cucumerinum* (Ali *et al.* 2008).

Table 7. Chemical Compounds and Their Relative Contents in Toon Wood Flour

Wood Species	Chemical Component	Relative Content (%)
Toon	Catechol	7.51
	Vanillin	2.15
	α-Muurolene	2.10
	d-Cadinene	3.40
	3-Hydroxy-4-methoxybenzoic acid	5.81
	1,6-Dimethyl-4-propan-2-ylnaphthalene	8.49
	3,4-Dihydroxybenzoic acid	3.56
	Methyl palmitate	3.85
	Palmitic acid	12.14
	Octadecanoic acid	2.55
	9-Octadecenamide, (Z)-	2.08
	4-Methoxy-4',5'-methylenedioxybiphenyl-2-carboxylic acid	6.03
	γ-Sitosterol	23.37
	Cycloeucalenol	16.97

Fifteen compounds were found in the sweetgum wood extractive (Table 8). There were two main components consisting of syringic acid (19.87%) and 5-hydroxymethyl-furfural (15.19%). Syringic acid is an active phenolic compound, which has been reported to possess anti-diabetic, antibacterial, and antifungal properties towards *Botrytis cinerea* and *Ganoderma boninense* (Chong *et al.* 2012; Mendoza *et al.* 2016). 5-Hydroxymethyl-furfural is an organic compound with a special fragrance, which serves as a nutritional source for fungi. It promotes and interferes with the growth of microorganisms, which has a negative effect on the fungal durability of sweetgum wood (Rosatella *et al.* 2011; Van Putten *et al.* 2013). In addition, six compounds, including vanillin (5.84%), syringaldehyde (8.69%), 4-hydroxy-3-methoxycinnamaldehyde (5.82%), palmitic acid (8.57%), 3,5-dimethoxy-4-hydroxycinnamaldehyde (2.78%), and *γ*-sitosterol (6.55%), were likely responsible for the resistance of the sweetgum wood against mold attack. Of these compounds, vanillin, palmitic acid, 4-hydroxy-3-methoxycinnamaldehyde, and *γ*-sitosterol were also present in other wood flour extractives and showed antifungal properties. Syringaldehyde is a phenolic compound, which exhibited antifungal activity against *Leucoagaricus gongylophorus* (De Souza *et al.* 2005). The 3,5-dimethoxy-4-hydroxy-cinnamaldehyde significantly affected the fungal growth and metabolism, which suggests that this molecule can be developed as an antifungal agent (Shreaz *et al.* 2013). Overall, the final mold resistance of sweetgum wood could be attributed to the synergistic action arising from the positive and negative effects provided by these antifungal components and 5-hydroxymethylfurfural, respectively.

Table 8. Chemical Compounds and Their Relative Contents in Sweetgum Wood Flour

Wood Species	Chemical Component	Relative Content (%)
Sweetgum	Catechol	1.62
	5-Hydroxymethylfurfural	15.19
	Vanillin	5.84
	3-Hydroxy-4-methoxybenzoic acid	7.25
	3,4,5-Trimethoxyphenol	2.69
	Syringaldehyde	8.69
	4-Hydroxy-3-methoxycinnamaldehyde	5.82
	Syringic acid	19.78
	Palmitic acid	8.57
	3,5-Dimethoxy-4-hydroxycinnamaldehyde	2.78
	Octadecanoic acid	7.21
	Cinnamic acid cinnamyl ester	4.26
	1-Docosanol	2.37
	γ-Sitosterol	6.55
	Stigmastanol	1.37

Twelve chemical components were found in the teak wood extractives (Table 9). Four main components with relatively high contents were 2-methylanthraquinone (22.50%), 2-hydroxymethylanthraquinone (18.36%), palmitic acid (10.75%), and squalene (10.74%). The compounds responsible for mold resistance were 2-hydroxymethyl-anthraquinone, vanillin (8.65%), palmitic acid, *γ*-sitosterol (8.75%), and cycloeucalenol (8.98%). Of these, 2-hydroxymethylanthraquinone possess some antifungal properties and plays an important role against the production of *A. niger* (Sumthong 2007).

Table 9. Chemical Compounds and Their Relative Contents in Teak Wood Flour

Wood Species	Chemical Component	Relative Content (%)
Teak	Vanillin	8.65
	4-((1E)-3-Hydroxy-1-propenyl)-2-methoxyphenol	1.48
	Palmitic acid	10.75
	N-(2-nitrosoacenaphthylen-1-yl)hydroxylamine	1.69
	2-Methylanthraquinone	22.50
	Methyl 10-trans,12-cis-octadecadienoate	3.09
	2-Hydroxymethylanthraquinone	18.36
	Squalene	10.74
	(E,E,E)-geranylgeraniol	1.55
	Stigmasterol	3.45
	γ-Sitosterol	8.75
	Cycloeucalenol	8.98

Thirteen compounds were identified in the wood extractives of *E. grandis* × *E. urophylla*, the main ones being palmitic acid (28.01%) and *γ*-sitosterol (17.62%) (Table 10). Both inhibited the mycelial growth of mold and decay fungi. In addition, vanillin (4.68%), syringaldehyde (4.80%), and syringic acid (2.11%) were also instrumental in the improvement of the resistance against fungal attack.

Table 10. Chemical Compounds and Their Relative Contents in *E. grandis* × *E. urophylla* Wood Flour

Wood Species	Chemical Component	Relative Content (%)
E. grandis × *E. urophylla*	Vanillin	4.68
	3-Hydroxy-4-methoxybenzoic acid	5.32
	Syringaldehyde	4.80
	Heptadecane	2.53
	4-((1E)-3-Hydroxy-1-propenyl)-2-methoxyphenol	3.82
	Syringic acid	2.11
	Palmitic acid	28.01
	Heptadecanoic acid	7.19
	Octadecanoic acid	5.85
	1-Heptacosanol	2.78
	4-Methoxy-4',5'-methylenedioxybiphenyl-2-carboxylic acid	8.84
	γ-Sitosterol	17.62
	Stigmastanol	6.44

As for *E. urophylla* wood extractives, syringaldehyde (22.76%), vanillin (13.70%), 4-hydroxy-3-methoxycinnamaldehyde (12.28%), syringic acid (4.35%), benzyl alcohol (2.06%), and *γ*-sitosterol (1.42%) were the key compounds responsible for fungal resistance (Table 11). These six compounds were also present in the other wood flour extractives, and the antifungal activities were described above. As a result, the final resistance of *E. urophylla* wood to the molds is the comprehensive effect of these compounds.

Table 11. Chemical Compounds and Relative Contents in *E. urophylla* Wood Flour

Wood Species	Chemical Component	Relative Content (%)
E. urophylla	Benzyl alcohol	2.06
	Benzaldehyde dimethyl acetal	3.24
	2,6-Dimethoxyphenol	1.64
	Vanillin	13.70
	Apocynin	2.54
	3-Hydroxy-4-methoxybenzoic acid	22.16
	Syringaldehyde	22.76
	4-Hydroxy-3-methoxycinnamaldehyde	12.28
	Syringic acid	4.35
	3,5-Dimethoxy-4-hydroxycinnamaldehyde	9.51
	Octadecanoic acid	2.62
	E-15-Heptadecenal	1.70
	γ-Sitosterol	1.42

The total contents of antifungal compounds in all the wood flour extractives were 80.97% in spruce wood, 60.88% in Mongolian pine, 19.63% in castor fiber, 60.68% in camphor wood, 60.29% in toon wood, 42.84% in sweetgum wood, 55.49% in teak wood, 57.74% in *E. grandis* × *E. urophylla* wood, and 56.57% in *E. urophylla* wood. This result was consistent with the sequence of resistance towards molds of different wood flours. This suggested that the natural durability of wood flour against fungi could be affected by their chemical components that could provide potentially positive or negative effects on the susceptibility or resistance to fungi.

CONCLUSIONS

1. Visual and SEM observations revealed that there were large differences in mold resistances between the nine wood flour species. The sequence of mold resistance of different wood flours is as follows: spruce > Mongolian pine and camphor > toon and teak > *eucalyptus* (*E. urophylla* and *E. grandis* × *E. urophylla*) > sweetgum > castor straw fiber.
2. The GC-MS analysis illustrated that the total content of the antifungal compounds present in all wood flour extractives were 80.97% in spruce, 60.88% in Mongolian pine, 19.63% in castor fiber, 60.68% in camphor, 60.29% in toon, 42.84% in sweetgum, 55.49% in teak, 57.74% in *E. grandis* × *E. urophylla*, and 56.57% in *E. urophylla*. This was well consistent with the sequence of mold resistance of different wood flour samples and suggested that the natural durability of wood flour against fungi could be significantly affected by their chemical composition.

ACKNOWLEDGMENTS

The authors are grateful for the support of the Science and Technology Planning Project of Guangdong Province, China (Grant No. 2015A010105019 and 2015A030302056) and the Science and Technology Planning Project of Guangzhou City, China (Grant No. 201604016096).

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Article submitted: November 29, 2017; Peer review completed: February 25, 2018; Revised version received: April 7, 2018; Accepted: April 8, 2018; Published: July 11, 2018.
DOI: 10.15376/biores.13.3.6524-6541