Comparison of resistance improvement to fungal growth on green and conventional building materials by nano-metal impregnation

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A R T I C L E   I N F O

Article history:
Received 3 May 2015
Received in revised form 15 June 2015
Accepted 17 June 2015
Available online 20 June 2015

Keywords:
Antifungal ability
Aspergillus
Penicillium
Nano-metal
Building material

A B S T R A C T

This study is aimed for comparing the biological resistance of green and conventional building materials (BMs) before and after nano-metal treatment, as well as exploring best nano-metals to improve fungal growth resistance of BMs. The selected BMs include wooden flooring (WF), green wooden flooring (GWF), gypsum board (GB), calcium silicate board (CSB), green calcium silicate board (GCSB), mineral fiber ceiling (MFC) and green mineral fiber ceiling (GMFC). The Aspergillus brasiliensis or Penicillium funiculosum was inoculated on each sample and their growth was visually evaluated according to ASTM G21-09.

The fungal growth without nano-metals on test materials did not show that green materials were more prone to fungal growth. After nano-metal treatment, the observed order of fungal growth resistance of nano-metals at their highest selected concentrations on test materials was nano-zinc = nano-copper > nano-silver for WF and GWF, nano-zinc > nano-silver = nano-copper for GB, nano-zinc > nano-silver > nano-copper for GGB, CSB and GCSB, nano-silver > nano-copper > nano-zinc for MFC, and nano-silver > nano-copper > nano-zinc for GMFC. Nano-zinc seems to be the most favorable nano-metal for wood and wood composite materials. Green materials were less resistant to fungi attack relative to their conventional counterparts treated by nano-metals, particularly GWF and WF. All test nano-metals failed to provide complete protection against fungal growth on the eight test BMs at the selected concentrations. However, the higher the nano-metal concentration was, the longer the lag period until growth began and fewer fungi grew on the materials.

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1. Introduction

Due to global climate change, extremely heavy rains and floods become more and more frequent worldwide, such as Hurricanes Katrina and Rita in the Gulf Coast of the United States, and Typhoon Morakot in southern Taiwan. Serious water damages and dampness in buildings have caused heavy fungal growth on building materials [1–6]. Fungal propagation can adversely affect the health of building occupants, including allergic symptom asthma, bronchi pulmonary aspergillosis and respiratory infection [7–17], and cause discoloration and deterioration of building materials [18–21].

Many studies have shown that fungi can easily grow on a variety of building materials, including conventional and green building materials [15,22,23]. Factors that affect fungal growth include moisture, material type, spore levels and fungal species [15,19,22,24–27]. Moisture has an impact on microbial growth by increasing both the concentration and diversity of microorganisms on water damaged surfaces [28–30]. Besides moisture, the main reason is that building materials such as ceiling tiles and wood materials which are organic compounds that can provide sufficient nutrients to support fungal growth whether the building material is labeled as green or conventional [23,31,32]. Correlations between building material types and fungal species present have been explored in some studies. Species of Penicillium are commonly found in various building materials [33–36]. Aspergillus species are frequently recovered on ceramic-type materials (concrete, mortar) and glues and paints [34,36]. Conventional antifungal additives to prevent fungal growth are often added in building materials, such as sodium polyborate, dichlofluanid, and so on [32,37–40]. However, the popularity of antifungal additives for indoor uses is limited due to its short-term effectiveness and potential health concerns.

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http://dx.doi.org/10.1016/j.buildenv.2015.06.016
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Nano-metals with enhanced properties compared to conventional ones. Specific characteristics of nano-metals include high surface to volume ratio, homogeneous particles size distribution, possibility of facile surface medication, good stability and the ease of preparation. These unique properties offer nano-metals great application in many fields. For example, nano-metals (e.g., silver, copper and zinc) have been widely applied to improve the physical and mechanical properties of various materials, such as paper, archaeological stones, coatings, woods and wood composites [41–49]. It is generally believed that nanoparticles of these metals interact with the bacterial membrane elements, resulting in the structural changes leading to the cell death. Also, these nanoparticles are small enough to damage cell membranes and further disrupt the enzyme function [50,51]. In addition, photocatalytic particles are small enough to damage cell membranes and further structural changes leading to the cell death. Also, these nano-particles interact with the bacterial membrane elements, resulting in the oxidation by TiO2 are often used to deactivate biological pollutants. Nevertheless, the correct use of nanomaterials not only offer strong antibacterial activity and low toxicity towards mammalian cells, but also provide a great potential in adsorption and degradation of environmental pollutants as they exhibit catalytic activity [61].

Although many studies about fungal growth or impact factors for fungal growth on building materials have been performed, such as quartz/putty [62], wood [63], cement based board and gypsum plaster board [64], ceiling tiles and wallboard cabinetry [23], studies on the biological resistance comparison of nano-metals on both conventional and green building materials are rather few. In this study, the biological resistance of green and conventional building materials (BMs) was compared before and after impregnation of single kind of nano-metal (i.e., Ag, Cu, and Zn) on Aspergillus brasiliensis (BCRC 31512) and Penicillium funiculosum (BCRC 30438) were tested which are ubiquitous in indoor air environment and can cause negative human health effects. The selected building materials include wooden flooring (WF), green wooden flooring (GWF), gypsum board (GB), green gypsum board (GGB), calcium silicate board (CSB), green calcium silicate board (GCSB), mineral fiber ceiling (MFC) and green mineral fiber ceiling (GMFC). This study will provide useful information for comparing the green and conventional materials in terms of fungal growth resistance before and after nano-metal treatment. It also helps choose best nano-metals to improve fungal resistance of buildings materials.

2. Experimental methodology

2.1. Building materials

Four different conventional materials and green counterpart for each conventional material were tested: wooden flooring (WF), green wooden flooring (GWF), calcium silicate board (CSB), green calcium silicate board (GCSB), gypsum board (GB), green gypsum board (GGB), mineral fiber ceiling (MFC), and green mineral fiber ceiling (GMFC). “Green” specifically refers to low emission healthy building materials which are rated by Taiwan Architecture and Building Center [52]. All materials were unused and were shipped directly from three major manufacturers in Taiwan. Materials were wrapped in two layers of aluminum foil and one layer of plastic sheeting before experiments carried out. Table 1 provides information on the basic composition and density of the test materials.

All selected materials are commonly used for ceiling, cabinetry, and flooring. Each specimen of BM was cut into identical sizes (5 cm × 5 cm) for testing. The thickness is 0.9 cm, 0.6 cm, 0.9 cm, 0.7 cm, 1.1 cm, 1.2 cm and 1.2 cm for GCSB, CSB, MFC, GGB, GB, GMFC, WF, and GWF, respectively. Prior to testing, the specimens were sterilized by Portable Auto Caves (Tuttnera, TM-328) at a temperature of 100–121 °C for 15 min.

2.2. Determination of specific surface area and total pore volume

Specific surface area and total pore volume of samples were obtained by Brunauer–Emmett–Teller (BET) method using BELSORP analysis software. Each sample was analyzed by automatic specific surface area/pore size distribution and chemisorption instrument (BELSORP-minii). The principle of the measurement is based on gas volume absorbed on solid surface of samples. Specific surface area and porosity of sample were determined by analyzing the capacity of absorbing liquid nitrogen gas via solid surface. Sample was degassed at 105 °C for 2 h before sample analysis in order for BELPREP-flow II to remove the water molecules on the sample surface. Then, each treated sample of 0.2 g was measured by microbalance and then poured into a special glass tube. In the end, each sample in the special tube was analyzed by BELSORP-mini II operation.

2.3. Water-holding capacity

The water-holding capacity (WHC) of each material was determined by submerging specimens (sized 5 cm × 5 cm) into water until fully saturated. The WHC of the samples was estimated by Eq. (1).

\[
\text{WHC} = \left( \frac{M_{\text{final}} - M_{\text{initial}}}{M_{\text{initial}}} \right) \times 100\%
\]

(1)

Where WHC is the water-holding capacity (%); \(M_{\text{initial}}\) is the initial mass of dry material (g) and \(M_{\text{final}}\) is the mass of fully saturated material (g). All measurements were in triplicate. The mean and standard deviation values were calculated.

2.4. Fungal species

Freezed-dried strains of A. brasiliensis (BCRC 31512) and P. funiculosum (BCRC 30438) were purchased from Bioresource Collection and Research Center (BCRC) in Taiwan. They were activated followed the description in the BCRC product instruction sheet before use. After being activated, each of the culture was transferred to the different potato dextrose agar plate and then incubated in incubation chamber at a temperature of 28–30 °C and 85% RH for 14 days in preparation of two spore suspensions. The concentration of A. brasiliensis spores in the first suspension was around 2 × 10⁹ CFU/mL, and the concentration of P. funiculosum spores in the second suspension was also around 2 × 10⁹ CFU/mL.

2.5. Inoculation of test specimens without nano-metals

A volume of 3 mL of each spore suspension was sprayed onto one surface of each test specimen in triplicate by using an airbrush attached to a mini-compressor with a pressure regulator with water separator. The non-inoculated area of the material surface served as a negative control area. The inoculated samples were then placed in petri dishes covered with a lid and finally incubated in...
incubation chamber at a temperature of 28–30 °C and 85% RH for 35 days. In comparison with JIS Z 2911 and ASTM G21-09 methods which do not simulate high humidity (e.g. soaked in water) and the incubation period is only up to 28 days, all specimens in this study were soaked in water for 4 h first and then put into incubation chamber at a temperature of 28–30 °C and 85% RH for 35 days for mold growth observation. The A. brasilienis or P. funiculosum growth on each sample was visually evaluated according to the rating scale described in ASTM G21-09 shown in Table 2.

2.6. Inoculation of test specimens with nano-metals

Single kind of nano-metal of Ag (AL-576832-5G, 99.5% particle size <100 nm), Cu (AF-45504-5G, APS 20–40 nm 99.9%), or Zn (AL-578002-5G, particle size <50 nm) was dissolved in distilled deionized water. Due to the limitation required by Toxicity characteristic leaching procedure according to NIEA R201.14C in Taiwan, the heavy metals including Ag and Cu leached from all green building material shall not exceed 0.05 mg/L and 0.15 mg/L. Thus, the prepared nano-metals solution were 0.01 g/L, 0.02 g/L, and 0.03 g/L for nano-Ag, and 0.05 g/L, 0.08 g/L and 0.10 g/L for nano-Cu. In the meantime, the prepared nano-Zn solution was higher with the values of 0.05 g/L, 0.15 g/L, 0.30 g/L and 0.60 g/L since there is no applicable restriction. The resultant solution was stirred to well mix for 2 h. After that, each material specimen in triplicate was soaked in each of the above prepared nano-metals solution by impregnation combined with ultrasonic cleaner (DELTA-DC400) for 30 min. Then, each material specimen soaked in nano-metals solution was taken out to dry for 10 min and placed in petri dishes.

A volume of 3 mL of each spore suspension was sprayed onto one surface of each test specimen in triplicate by using an airbrush attached to a minicompressor with a pressure regulator with water separator. The non-inoculated area of the material surface served as a negative control area. Each specimen in a petri dish was then essentially incubated in incubation chamber at a temperature of 28–30 °C and 85% RH for 35 days. The A. brasilienis or P. funiculosum growth on each sample was visually evaluated according to the rating scale described in ASTM G21-09 shown in Table 2.

2.7. Validation of ratings

The fungi growth assessment above is somewhat subjective to evaluate the extent of fungi. Numerical values cannot be obtained based on human judgment. Thus, cells on each material specimen on which fungi growth has been assessed according to Table 2 were counted by a Hemocytometer (MARIENFELD, 0.0025 mm², Germany). Cells counting on each kind material specimen for each rating judged by human were averaged and the standard deviation was provided as well.

3. Results and discussion

3.1. Physical properties of test materials

In Table 3, the results show that CSB and GCSB had the highest specific surface area and total pore volume. Conventional and corresponding green pairs had similar specific surface area and total pore volume. However, specific surface area values between MFC and GMFC and total pore volume values between GB and GGB showed significant variations. CSB and GCSB had the slightly lower WHC values (about 60%). MFC, GMFC, GB, GGB, WF and GWF all had essentially similar level of WHC, comparable to the WHC values measured by Hoang et al. [23] for bamboo flooring, gypsum board, drywall, inorganic ceiling tile and particle board. High pore volume is beneficial for oxygen transport, high WHC is easy to hold water needed for fungi growth and high surface area is good for fungi attachment.

3.2. Inoculation of test specimens without nano-metals

A. brasilienis and P. funiculosum cells counting on each kind material specimen for each rating was shown in Table 4. Average cells counting of A. brasilienis at rating 1 to 4 on all test materials are increasing and they are 6.81 × 10⁹/m³, 1.69 × 10⁹/m³, 2.39 × 10⁹/m³ and 3.66 × 10⁹/m³, respectively. Average cells counting of P. funiculosum at rating 1 to 4 on all test materials are also increasing and they are 6.72 × 10⁹/m³, 1.43 × 10⁹/m³, 2.12 × 10⁹/m³ and 3.02 × 10⁹/m³, respectively. Thus, it is suggested that the fungi growth assessment by human judgment is reasonable. However, cells counting at same rating varied among different materials. This may be explained by different physical properties of materials themselves.

After being incubated in incubation chamber at a temperature of 28–30 °C and 85% RH for 35 days, fungal growth at rating 2 was observed on the non-inoculated surface area of GWF and GGB. Slight fungal growth at rating 1 was observed on the non-inoculated surface area of WF and GB (Fig. 1). After being artificially inoculated the A. brasilienis or P. funiculosum and incubated in chamber for 35 days, almost all building materials showed P. funiculosum growth at rating 4 after 28 days (Fig. 2). Extensive P. funiculosum growth at rating 4 was observed on GMFC, GB, GWF, MFC, WF, GGB, CSB and GCSB after 16, 17, 18, 19, 26, 27 and 28 days, respectively. It seems that green materials were not necessarily more resistant, nor more prone to fungal growth than their
conventional counterparts, consistent with the findings of Hoang et al. [23]. Moreover, *A. brasiliensis* grows faster than *P. funiculosum* given *A. brasiliensis* growth at rating 2 after only 7 days and growth at rating 4 after 25 days (Fig. 3). Extensive *A. brasiliensis* growth at rating 4 was observed on MFC, GWG, GMFC, WF, GGB, CSB and GCSB after 11, 15, 21, 23, 24, 24, 25 and 25 days, respectively. Thus, it seems that MFC, GMFC, WF and GWF have faster fungal growth than GB, GGB, CSB and GCSB.

### 3.3. Inoculation of Test Specimens with Nano-Silver

After being soaked in nano-silver solution [with concentrations of 0.01 g/L, 0.02 g/L and 0.03 g/L] and inoculated the *A. brasiliensis* or *P. funiculosum*, the fungal growth on each of test material for 35 days was shown in Supplementary material. In general, nano-silver used in this study failed to provide complete protection against fungal growth on the eight test building materials at the selected concentrations. However, the higher the nano-metal concentration was, the longer the lag period until growth began and less fungi grew on the materials.

For nano-silver concentration of 0.01 g/L, there was no *P. funiculosum* growth during the first four days and no *A. brasiliensis* growth during the first two days. Fungal growth at rating 1 and rating 2 were observed on all test materials within 6 days and 20 days, respectively. Growth of *P. funiculosum* on GB and *A. brasiliensis* on GMFC, GB, GGB, WF stayed at rating 2 after 35 days. For nano-silver concentration of 0.02 g/L, there was no fungal growth during the first four days. Fungal growth at rating 1 and rating 2 were observed on all test materials within 6 days and 17 days, respectively. Growth of *P. funiculosum* on WF, GB, GGB and *A. brasiliensis* on GMFC, GB, GWF, MFC stayed at rating 2 after 35 days. For nano-silver concentration of 0.03 g/L, there was no fungal

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**Table 3**

Physical properties of test materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific surface area (m²/g)</th>
<th>Total pore volume (cm³/g)</th>
<th>Water-holding capacity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WF</td>
<td>$8.18 \times 10^{-2} \pm 1.11 \times 10^{-2}$</td>
<td>$2.38 \times 10^{-3} \pm 0.01 \times 10^{-3}$</td>
<td>83.2 ± 0.6</td>
</tr>
<tr>
<td>GWF</td>
<td>$8.24 \times 10^{-2} \pm 0.91 \times 10^{-2}$</td>
<td>$2.46 \times 10^{-3} \pm 0.01 \times 10^{-3}$</td>
<td>80.3 ± 0.7</td>
</tr>
<tr>
<td>GB</td>
<td>1.11 ± 0.03</td>
<td>2.33 ± 10^{-2} ± 0.02 × 10^{-2}</td>
<td>71.3 ± 0.5</td>
</tr>
<tr>
<td>GGB</td>
<td>1.29 ± 0.05</td>
<td>7.66 ± 10^{-2} ± 0.05 × 10^{-2}</td>
<td>76.3 ± 0.5</td>
</tr>
<tr>
<td>CSB</td>
<td>27.25 ± 0.12</td>
<td>0.29 ± 0.02</td>
<td>59.6 ± 0.4</td>
</tr>
<tr>
<td>GCSB</td>
<td>34.87 ± 0.26</td>
<td>0.29 ± 0.02</td>
<td>60.2 ± 0.4</td>
</tr>
<tr>
<td>MFC</td>
<td>6.46 ± 0.031</td>
<td>3.14 ± 10^{-2} ± 0.03 × 10^{-2}</td>
<td>80.3 ± 0.6</td>
</tr>
<tr>
<td>GMFC</td>
<td>1.12 ± 0.014</td>
<td>2.12 ± 10^{-2} ± 0.02 × 10^{-2}</td>
<td>83.0 ± 0.6</td>
</tr>
</tbody>
</table>

Note: Results are shown as the mean value ± standard deviation. “WF” refers to wooden flooring; “GB” refers to gypsum board; “CSB” refers to calcium silicate board; “MFC” refers to mineral fiber ceiling; “GWF” refers to green wooden flooring; “GGB” refers to green gypsum board; “GCSB” refers to green calcium silicate board; “GMFC” refers to green mineral fiber ceiling.

**Table 4**

Cells counting on each kind material specimen for each rating.

<table>
<thead>
<tr>
<th>Fungal Rating</th>
<th>Cells (#/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WF</td>
</tr>
<tr>
<td>A 1</td>
<td>7.75 × 10^8</td>
</tr>
<tr>
<td>2</td>
<td>2.03 × 10^9</td>
</tr>
<tr>
<td>3</td>
<td>3.00 × 10^9</td>
</tr>
<tr>
<td>P 4</td>
<td>3.55 × 10^9</td>
</tr>
<tr>
<td>2</td>
<td>8.75 × 10^8</td>
</tr>
<tr>
<td>3</td>
<td>1.98 × 10^9</td>
</tr>
<tr>
<td>4</td>
<td>2.63 × 10^8</td>
</tr>
</tbody>
</table>

Note: “A” refers to Aspergillus; “P” refers to Penicillium.

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![Fig. 1. Fungal growth on non-inoculated surface area of building materials.](image1.png)

![Fig. 2. Growth of Penicillium on building materials without nano-metals.](image2.png)
growth during the first seven days. In addition, no fungal growth at rating 4 was observed on any test material. Fungal growth at rating 1 was observed on all test materials within 6 days. Growth of *P. funiculosum* on GCSB, GMFC, WF, CSB and *A. brasiliensis* on MFC, GMFC, GB and GGB stayed at rating 1 after 35 days.

Fungal growth ratings for building materials impregnated with nano-silver after 35 days were shown in Tables 5 and 6. For *Penicillium* growth on materials with nano-silver, the results showed improved fungal growth resistance on all test materials relative to control tests. Resistance to *Penicillium* growth on GWF was not enhanced obviously at the selected concentrations of nano-silver in this work (Table 5). For *Aspergillus* growth on materials with nano-silver, improved fungal growth resistance was also observed on all test materials relative to control tests. Resistance to *Aspergillus* growth on GWF was not enhanced obviously, similar to the results for *Penicillium*. However, *Aspergillus* growth on CSB and GCSB was not significantly inhibited (Table 6).

### 3.4. Inoculation of test specimens with nano-Copper

After being soaked in nano-copper solution (with concentrations of 0.05 g/L, 0.08 g/L and 0.1 g/L) and inoculated the *A. brasiliensis* or *P. funiculosum*, the fungal growth on each of test material for 35 days were shown in Supplementary material. In general, nano-copper used in this study failed to provide complete protection against fungal growth on the eight test building materials at the selected concentrations. However, the higher the nanometal concentration was, the longer the lag period until growth began and fewer fungi grew on the materials.

For nano-copper concentration of 0.05 g/L, there was no fungal growth during the first three days. Fungal growth at rating 1 and 2 were observed on all test materials within 6 days and 18 days, respectively. Growth of *P. funiculosum* on GB stayed at rating 2 after 35 days. For nano-zinc concentration of 0.15 g/L, there was no fungal growth during the first three days. Fungal growth at rating 1 and 2 were observed on all test materials within 6 days and 27 days, respectively. Growth of *P. funiculosum* on WF and *A. brasiliensis* on GCSB, CSB, GB and WF stayed at rating 2 after 35 days. For nano-copper concentration of 0.60 g/L, there was no fungal growth during the first three days. Fungal growth at rating 1 was observed on all test materials within 6 days. Growth of *P. funiculosum* on GGB, MFC and *A. brasiliensis* on WF stayed at rating 1 after 35 days. For nano-zinc concentration of 0.08 g/L, there was no fungal growth during the first four days. Fungal growth at rating 1 was observed on all test materials within 6 days. Growth of *P. funiculosum* on GGB, MFC and *A. brasiliensis* on WF stayed at rating 1 after 35 days. For nano-copper concentration of 0.08 g/L, there was no fungal growth during the first four days. Fungal growth at rating 1 was observed on all test materials within 7 days. Growth of *P. funiculosum* on GB and *A. brasiliensis* on WF stayed at rating 1 after 35 days. For nano-copper concentration of 0.1 g/L, there was no fungal growth during the first four days. Fungal growth at rating 1 was observed on all test materials within 6 days. Growth of *P. funiculosum* on WF, GB and *A. brasiliensis* on WF stayed at rating 1 after 35 days.

Fungal growth ratings for building materials impregnated with nano-copper after 35 days were shown in Tables 5 and 6. For *Penicillium* growth on materials with nano-copper, the results only showed improved fungal growth resistance on GWF, WF, GB and GGB relative to control tests, while no significant fungal resistance effect of nano-copper was observed on CSB, GCSB, MFC and GMFC at the selected concentrations of nano-copper in this work (Table 5). For *Aspergillus* growth on materials with nano-copper, improved fungal growth resistance ability was observed on all test materials relative to control tests. Thus, it seems that nano-copper works better to resist *Aspergillus* than *Penicillium* on CSB, GCSB, MFC and GMFC (Table 6).

### 3.5. Inoculation of test specimens with nano-Zinc

After being soaked in nano-zinc solution (with concentrations of 0.05 g/L, 0.15 g/L, 0.30 g/L and 0.60 g/L) and inoculated the *A. brasiliensis* or *P. funiculosum*, the fungal growth on each of test material for 35 days were shown in Supplementary material. In general, nano-zinc used in this study failed to provide complete protection against fungal growth on the eight test building materials at the selected concentrations. However, the higher the nanometric concentration was, the longer the lag period until growth began and fewer fungi grew on the materials.

For nano-zinc concentration of 0.05 g/L, there was no fungal growth during the first three days. Fungal growth at rating 1 and 2 were observed on all test materials within 6 days and 18 days, respectively. Growth of *P. funiculosum* on GB stayed at rating 2 after 35 days. For nano-zinc concentration of 0.15 g/L, there was no fungal growth during the first three days. Fungal growth at rating 1 and 2 were observed on all test materials within 6 days and 27 days, respectively. Growth of *P. funiculosum* on WF and *A. brasiliensis* on GCSB, CSB, GB and WF stayed at rating 2 after 35 days. For nano-zinc concentration of 0.30 g/L, there was no fungal growth during the first three days. Fungal growth at rating 1 was observed on all test materials within 8 days. Growth of *P. funiculosum* on MFC, WF stayed at rating 1 after 35 days. For nano-zinc concentration of 0.60 g/L, there was no fungal growth during the first seven days. Fungal growth at rating 1 was observed on all test materials within

### Table 5

*Penicillium* growth ratings on building materials impregnated with nano-metals after 35 days.

<table>
<thead>
<tr>
<th>Nano-metals</th>
<th>Concentration (g/L)</th>
<th>WF</th>
<th>GWF</th>
<th>GB</th>
<th>GGB</th>
<th>CSB</th>
<th>GCSB</th>
<th>MFC</th>
<th>GMFC</th>
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<tr>
<td>Control</td>
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18 days. Growth of *P. funiculosum* on GGB, WF, CSB, GB and *A. brasiliensis* on GCSB, WF, CSB, GGB and GB stayed at rating 1 after 35 days.

Fungal growth ratings for building materials impregnated with nano-zinc after 35 days were shown in Tables 5 and 6. For Penicillium growth on materials with nano-zinc, the results showed improved fungal growth resistance on all test materials relative to control tests. Resistance to *Penicillium* growth on GMFC was not enhanced obviously (Table 5). For *Aspergillus* growth on materials with nano-zinc, improved fungal resistance was observed on all test materials except MFC and GMFC (Table 6).

### 4. Discussion

The results of building material inoculation without nano-metals showed that MFC, GMFC, WF and GWF had faster fungal growth than GB, GGB, CSB and GCSB, probably due to their greater WHCs which help the materials absorb water very fast, leading to faster mold growth. In addition, MFC, GMFC, WF and GWF may work as better organic food sources that provide necessary nutrition for fungal growth [23,30,31].

Average fungal ratings for test building materials treated with nano-metals at the highest selected concentrations after 35 days were shown in Figs. 4−7. It can be seen that fungi grew at similar rates on green building materials relative to their conventional counterparts treated by nano-metals except that a lot more fungi were found on GWF than WF treated by any nano-metals in this study. A bit more fungi grew on GGB, GCSB and GMFC than their conventional counterparts treated by nano-copper, nano-zinc and nano-silver, respectively. Thus, although the fungi growth without nano-metals on test materials in this work did not show that green materials were more prone to fungal growth, they were less resistant to fungi attack relative to their conventional counterparts treated by nano-metals. The reason may be related to different interactions between green materials and nano-metals, leading to more fungal growth, which needs further study to identify. It is also demonstrated that the order of fungal growth resistance of nano-metals at their highest selected concentrations in this study on test materials was nano-zinc > nano-copper > nano-silver for WF and GWF, nano-zinc > nano-silver > nano-copper for GB, nano-zinc > nano-silver > nano-copper for GGB, CSB and GCSB, nano-silver > nano-copper = nano-zinc for MFC, and nano-silver > nano-copper > nano-zinc for GMFC.

Thus, for WF, GWF, GB, GGB, CSB and GCSB, nano-zinc is the most promising nano-metal to help protect them from fungi attack. Both Mantanis et al. [47] and Kartal et al. [42] used nano-zinc and nano-copper to evaluate termite and mold resistance on pine wood and wood. Their findings suggested that nano-zinc is more favorable in terms of leach resistance, termite mortality and inhibition of termite feeding and decay by the white-rot fungus. In addition, nano-zinc is the cheapest among the three nano-metals and its concentration is not limited by Toxicity characteristic leaching procedure according to NIEA R201.14C in Taiwan. Therefore, it seems that nano-zinc is the most favorable nano-metal for wood and wood composite materials. As for MFC and GMFC, nano-silver seems better to help resist fungal growth than the other two nano-metals in this work.

### 5. Conclusions

Although the fungi growth without nano-metals on test materials in this work did not show that green materials were more prone to fungal growth, they were less resistant to fungi attack relative to their conventional counterparts treated by nano-metals, especially GWF and WF. All test nano-metals in this study failed to provide complete protection against fungal growth on the eight test building materials at the selected concentrations. However, the higher the nano-metal concentration was, the longer the lag period until growth began and fewer fungi grew on the materials. Nano-zinc seems to be the most favorable nano-metal for wood and wood composite materials in this study.

Only four conventional and their green pair materials in Taiwan
were tested, further researches are needed to evaluate a bigger range of green and conventional building materials. It is beneficial to better understand the mechanisms of nano-metals affecting fungal growth on both green materials and their conventional counterparts. In addition, it may be desirable to identify interactions between green materials and nano-metals, leading to more fungal growth, which needs further study to identify main fungal species that grow on various building materials and to evaluate their growth and deterioration resistance on these materials treated with nano-metals. This study will provide useful information for comparing the green and conventional materials in terms of fungal growth resistance before and after nano-metal treatment. It also helps choose best nano-metals to improve fungal resistance of buildings materials.

Acknowledgments

The authors would like to thank Ministry of Science and Technology of the Republic of China for funding this research (under contract MOST 100-2221-E-390-002 and MOST 101-2221-E-390-010-MY3). We also wish to thank Dr. Ping Zhao for the help of English editing.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.buildenv.2015.06.016.

References


