EFFECT OF SILVER NANOPARTICLES ON WHITE-ROT WOOD DECAY AND SOME PHYSICAL PROPERTIES OF THREE TROPICAL WOOD SPECIES

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Abstract. Wood is one of the most widely used materials and is used in many applications. However, decay resistance of wood is limited in tropical conditions. Nanotechnology applications have potential for improving materials. In this study, a solution with a concentration of 50 ppm silver nanoparticles was incorporated by pressure into three commercial species (*Acacia mangium*, *Cedrela odorata*, and *Vochysia guatemalensis*) of Costa Rica. The white-rot fungus (*Trametes versicolor*) was tested, and some physical properties were also measured. According to the results, synthetized silver nanoparticles (10-25 nm) presented little agglomeration and were adequately distributed. The retention achieved was 25-102 silver mg/kg^{-1} of wood, varying among species and with presence of sapwood and heartwood. Mass loss was less than 5% in wood treated with silver nanoparticles; thus, the wood was classified as highly resistant or class A. Meanwhile, untreated wood presented losses greater than 20% with white-rot fungi. Also, water absorption capacity decreased for wood treated with silver nanoparticles in the three species tested, and dimensional stability increased for *Cedrela odorata* and *Vochysia guatemalensis* treated with silver nanoparticles.

Keywords: Wood preservatives, nanotechnology, tropical species, boric acid, sodium borate.

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INTRODUCTION

Nanotechnology is being intensively developed for a wide variety of applications, from material behavior improvement to medical uses (Scott and Chen 2013). Nanotechnology development has improved the properties of wood and the products derived from it (Tarmian et al 2012). Studies on wood nanotechnology applications focus on the following areas: 1) changes in physical and mechanical properties; 2) dimensional stability of wood; 3) changes in wood appearance (color) and resistance to outdoor conditions; and 4) resistance to the attack of micro-organisms. The interest in silver nanoparticles for different types of applications, among them medical applications because of their antibacterial activity, has grown worldwide (Mahapatra et al 2013). This type of nanoparticle has also gained popularity in plant biology (Anjum et al 2013), material reinforcement (Reidy et al 2013), and wood property improvement. The use in wood has the objective to enhance the physical and mechanical properties of wood and its durability and behavior before chemical substances or radiation (Mie et al 2013). Nanotechnology applications improve material properties and use only small quantities.

Silver nanoparticles have improved wood protection (Liu et al 2002a, 2002b, 2002c), behavior against fire (Taghiyari 2012), physical properties (Taghiyari 2012; Taghiyari and Bibalan 2013), thermal treatment (Taghiyari et al 2012), densification (Rassam et al 2012), particleboard production (Taghiyari et al 2011), and drying (Tarmian et al 2012).

There are different methods for synthetizing silver nanoparticles (Tan and Cheong 2013). The most important are reduction methods (Mavani and Shah 2013) using sodium borohydride ($NaBH_4$) as a silver reduction agent for synthesizing nanoparticles (Mavani and Shah 2013). The studies of effects of silver nanoparticles on wood fungi resistance properties (Liu et al 2002a, 2002b, 2002c; Akhtari et al 2013) do not offer a description of silver nanoparticle synthetizing methodologies. In addition, little is known about the effects on tropical woods. We believe that the synthesis of silver nanoparticles with $NaBH_4$ as a silver reduction agent has potential, because boron particles, an active wood preservative component (Lloyd 1998), are added in silver nanoparticle solution. Applications for bacterial growth control (Mavani and Shah 2013), wood protection (Schultz et al 2008), and human medicine (Crabtree et al 2003) have been studied.

This study reports on the synthetizing of silver nanoparticles by reduction with $NaBH_4$ and how silver nanoparticles effect wood absorption capacity, retention, resistance to the attack of *Trametes versicolor* (white-rot), density and specific gravity and dimensional stability (swelling).

MATERIALS AND METHODS

Materials

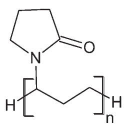
For nanoparticle synthetizing, three components were used: silver nitrate ($AgNO_3$) as a source of the reduced metal, supplied by Merck (White House Station, NJ) (99.9% purity), $NaBH_4$ as a reduction agent, supplied by Merck (99% purity), and polyvinylpyrrolidone (PVP) as a stabilizing agent, supplied by Magnacol Ltd. (Newtown, Wales, UK) The reaction was performed in an aqueous medium. Samples of three tropical wood species in Costa Rica were used: sapwood and heartwood of *Acacia mangium*, sapwood and heartwood of *Cedrela odorata*, and sapwood of *Vochysia guatemalensis*. The fungi tests were performed with the white-rot fungus *Trametes versicolor*.

Synthetizing Silver Nanoparticles

Silver nanoparticles were synthesized using the method described by Mavani and Shah (2013). It is based on a reduction reaction in which an excess of $NaBH_4$ as a reducing agent, PVP as a stabilizing agent, and $AgNO_3$ as the silver source are used. The reaction is carried out in an aqueous medium in an ice bath. This reaction involves taking 0.93 L of a solution of 0.015 M $NaBH_4$, which is stirred constantly within an ice bath. Then, the 0.015-M $NaBH_4$ solution is added to 0.90 mL of 3% PVP. After these two solutions ($NaBH_4$ and PVP) were homogenized, 62.8 mL of 0.0073-M $AgNO_3$ solution is added slowly (1 drop per second) until it presents a gold to brown coloration. More detail on the process of the reaction can be obtained from Mavani and Shah (2013), and the reaction of silver nitrate with sodium borohydride may be written as Eq 1. The reaction efficiency was not evaluated and was therefore considered to be a 100% conversion of silver nitrate to reduced silver. The concentration of silver nanoparticles in this solution was 50 ppm. PVP was used to protect the silver nanoparticles from agglomeration. This product was added to the solution without any treatment.

$$2AgNO_3 + 2NaBH_4 + 6H_2O \xrightarrow{PVP} 2Ag_0 + 2NaNO_3 + 2H_3BO_3 + 7H_2$$

PVP=



(1)

UV Observation and Transmission Electron Microscope Images

To perform the UV measurements, a sample was taken from the nanoparticle solution, which was then poured on the UV sample holder. The characterization was based on UV-visible spectroscopy (T18 manufactured by PG Instruments, Leicestershire, UK). The measurement was performed with respect to a blank of distilled water. A small sample was again taken to obtain the transmission electron microscope (TEM) images, which was then placed in the microscope using 100-kV acceleration and 10,000× (B and C) and 30,0000× (D) amplification. The images of the silver nanoparticles were observed with a JEOL (Akishima-Shi, Tokyo, Japan) TEM, JEM-2100 model. In the case of observation with atomic force microscopy (AFM), a 5-mL sample of the nanoparticle solution was taken, dissolved in 5 mL of ethanol, and then centrifuged for 5 min. Then, a small drop of this solution was observed in AFM on a ceramic surface and ethanol needed to evaporate to make the measurement. The asylum research model MFP 3D was used to take images of the AFM.

Preservation of Wood Samples with Silver Nanoparticles

Five 25-mm thick × 20-cm wide boards for each species were bought locally. The boards were dried to 12% MC in a room chamber at 22°C and 65% in RH. Afterward, 25-mm × 25-mm cross-section billets were cut from each board and separated in sapwood and heartwood. Then they were planed to 20 mm × 20 mm in cross-section and samples measuring 20 × 20 × 20 mm were prepared. Sixty heartwood samples and 60 sapwood samples each for *A. mangium* and *C. odorata* and 60 samples of sapwood for *V. guatemalensis* were randomly selected for testing. For the latter species, heartwood was not tested because it is not discernable in this species. All samples were placed into a 1-m^3 experimental pressure vessel commonly used for wood preservation. The preservation process consisted of 30 min of vacuum at –78 kPa (gauge), 2 h of pressure at 690 kPa, and 15 min of vacuum at –78 kPa (gauge). The samples were weighed before and after the preservation process. Absorption capacity for each sample was calculated as the absorption of solution in liters/timber volume. Nanosilver retention was determined by weight gain of the nanosilver solution.

Decay Resistance

The species tested were *Acacia magnium* (acacia), *Cedrela odorata* (cedro amargo), and *Vochysia guatemalensis* (cebo). The effectiveness of silver nanoparticles in these species was measured by the degradation of wood against fungal attack, specifically resistance to white decay (*Trametes versicolor*). A total of 30 samples of 20 × 20 × 20 mm of each species was injected with the nanoparticle solution by vacuum pressure (15 min of vacuum and 4 h of pressure). For each sample, the concentration of nanoparticles was calculated based on weight gain. These samples were oven-dried to 0% moisture and then placed into a desiccator with water for 2 wk. Thirty samples (20 × 20 × 20 mm) without any treatment were also conditioned and used as controls. This conditioning allowed the wood samples to reach 30% MC. Subsequently, the samples were sterilized and placed in a soil-block medium into bottles previously inoculated with the fungus, according to the ASTM D2017 Standard (ASTM 2003) and exposed for 4 months. The sample was then cleaned, oven-dried to determine the final weight, and weight loss calculated.

Specific Gravity, Density, and Moisture Content

Thirty samples (20 × 20 × 20 mm) each of untreated wood and nanosilver-treated wood per species were tested. The samples were placed in a conditioning chamber maintained at 12% equilibrium MC (22°C and 60% RH). Then, the treated and the untreated samples were weighed and their volume measured, and the samples were placed into an oven at 103°C for 24 h to reach the moisture-free mass. The following properties were determined: specific gravity based on sample volume and 12% MC (oven-dry weight/volume at 12%), density (weight at 12%/volume at 12%), and moisture content (water weight at 12% /oven-dry volume) were determined.

Swelling and Water Absorption

The remaining 30 samples (treated and untreated) were used to measure swelling and water absorption. Thirty 50-mm-wide × 50-mm-long × 12-mm-thick samples were obtained from the wood treated with silver nanoparticles, and their radial and tangential positions were adequately oriented. Likewise, 30 samples were extracted from the untreated wood with the same dimensions and also adequately oriented. The samples were immersed in water for 24 h at room temperature. Each sample was weighed, and their tangential and radial dimensions before and after immersion were measured. Lastly, the samples were placed in an oven at 103°C to determine their oven-dry weight. With this information, moisture content, radial and tangential swelling before and after drying, and percentage of absorbed water by the wood after the 24-h immersion were determined.

Statistical Analysis

A descriptive analysis was developed (mean and standard deviation) for absorption parameters (density of the wood and solution absorption and retention), properties of wood (weight loss, specific weight, and moisture content), and dimensional stability parameters (radial and tangential swelling, moisture content before and after immersion in water, and water absorption percentage). In addition, it was verified if the variables met the assumptions of normal distribution, homogeneity of variances, and the presence of extreme data. Subsequently, an analysis of variance was applied to verify the effect of treatment (two levels: treated and untreated) with the silver nanoparticles on the previously indicated properties of the wood of each species studied. Tukey's test was set at a 99% confidence level to determine the statistical difference between the means.

RESULTS AND DISCUSSION

Characterization of Nanoparticles

The silver nanoparticle synthesis method used in the investigation showed that the solution was unclear and had a light greenish yellow color. Nanoparticle size ranged from 10 to 25 nm (Fig 1a-b). AFM analysis shows the presence of nanoparticles in a solution and also gives evidence that the irregularity can reach 15 nm (Fig 1a). These measurements were confirmed by TEM, which allows the observation of nanoparticles with diameters up to 25 nm (Fig 1b). Particles were spherical in shape, and the largest ones were prismatic (Fig 1c). An important aspect is that although PVP was added to prevent agglomeration of particles, clustered areas (Fig 1d) occurred. Also, the UV-Vis spectrum of the nanoparticles showed a distinct band centered around 400 nm (Fig 1e).

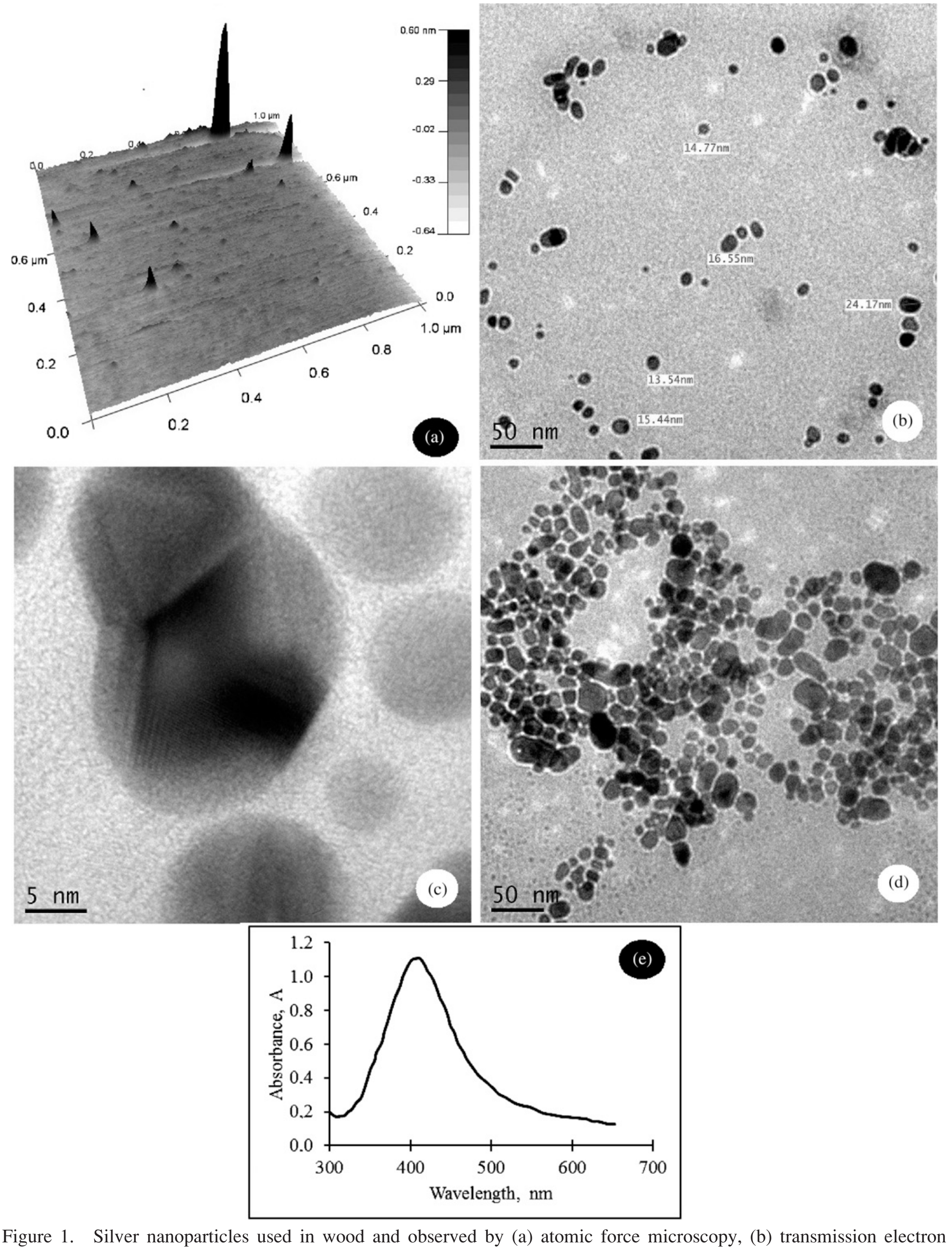


Figure 1. Silver nanoparticles used in wood and observed by (a) atomic force microscopy, (b) transmission electron microscopy, (c) shape of silver nanoparticles, (d) region of agglomerated silver nanoparticles, and (e) UV-vis spectrum of silver nanoparticles.

There are different synthetizing methods for silver nanoparticles. Among the most popular are those based on chemical reduction, photoreduction, and thermal decomposition (Mavani and Shah 2013). The method applied in this study, considered one of the simplest and most efficient (Mavani and Shah 2013), resulted in silver nanoparticles of adequate size and slight agglomeration (Fig 1), as demonstrated by the observations from the AFM (Fig 1a) and TEM (Fig 1b-d) and the measurements carried out with the UV-Vis spectrum. This last technique proves that most of the particles with sizes less than 50 nm are on the band above 400 nm, which was also demonstrated by Sileikaite et al (2006) and Prema and Raju (2009).

Absorption and Retention of Silver Nanoparticles

V. guatemalensis was the species with the highest capacity to absorb the solution, therefore the one to retain the most silver nanoparticles per volume of wood ($g_{Ag}/m^3{}_{wood}$) followed by *A. mangium*. Neither of these two species showed any difference between sapwood and heartwood absorption. The sapwood of *C. odorata* was the wood with the lowest capacity to absorb the solution and with the lowest retention of nanoparticles (Table 1). However, when absorption by wood mass was projected, the behavior was slightly different. *V. guatemalensis* showed greater retention followed by heartwood of *A. mangium* and sapwood of *C. odorata*, and then by sapwood of *A. mangium*, with a statistically lower retention than previous types of wood. Lastly, the heartwood of *C. odorata* had the statistically lowest value (Table 1).

The silver nanoparticle absorption values obtained, from 267 to 653 $L/m^3{}_{wood}$, were evidence that it is possible to use the vacuum-pressure method commonly used in the preservation of wood (Schultz et al 2007; Barnes 2008) with the solution of silver nanoparticles. However, further research is needed to evaluate the effect of the nanoparticle solution on the metallic and plastic components that are part of these preservation systems (Glover et al 2011).

The absorption obtained in the heartwood of *A. mangium* and *C. odorata* should be analyzed in detail, because the heartwood of most species is refractory (Lebow 2010). However, the absorptions of *A. mangium* and *C. odorata* were 514 and 267 $L/m^3{}_{wood}$, respectively, which are high compared with other tropical woods such as *Tectona grandis*, *Swietenia macrophylla*, *Cupressus lusitanica*, and *Gmelina arborea*. Those species are generally considered to be refractory to penetration of substances (Moya and Muñoz 2010). The high absorption may be explained first by the fact that wood of 20-mm maximum length was used, allowing a degree of longitudinal penetration in the wood (Islam et al 2008). Second, the heartwood of some species from tropical climates shows some degree of penetration with this method (Keenan and Tejada 1988; Stan 2010). This capability of absorbing a liquid or not is related to the anatomical structure and abundance and number of wood extractives (Stan 2010).

The value of absorption of silver nanoparticles solution in sapwood (Table 1) is considered rather high, similar to the absorption values presented by other tropical species, between 121 and 417 $L/m^3{}_{wood}$ (Moya and Muñoz 2010). The difference between these species was caused

Table 1. Absorption and retention of silver nanoparticles in treated and untreated wood of the species *Acacia mangium*, *Vochysia guatemalensis*, and *Cedrela odorata*.[a]

Species	Type of wood	Absorption ($L/m^3{}_{wood}$)	Retention of nanosilver ($g_{Ag}/m^3{}_{wood}$)	Retention of nanosilver (mg_{Ag}/kg_{wood})	Wood density before impregnation (g/cm^3)
Acacia mangium	Sapwood	497^A (12.41)	24.89^A (12.41)	45.75^A (15.31)	0.55^A (7.52)
	Heartwood	514^A (28.76)	25.75^A (28.76)	58.48^B (43.41)	0.48^B (20.96)
Cedrela odorata	Sapwood	510^A (8.03)	25.50^A (8.03)	54.35^B (11.94)	0.47^B (5.17)
	Heartwood	267^B (20.93)	13.36^B (20.93)	25.27^C (36.68)	0.55^A (11.19)
Vochysia guatemalensis	Sapwood	653^C (7.06)	32.66^C (7.06)	101.96^D (14.40)	0.33^C (12.67)

[a] Values in parentheses are coefficients of variation. Average values identified with A and B are statistically different at $\alpha = 99\%$.

by their differences in weight (Keenan and Tejada 1988). Woods with low specific weight, such as *V. guatemalensis*, have high absorption, whereas woods with higher specific weight such as *A. mangium* absorb less (Table 1).

Tropical woods with high absorption have the advantage of absorbing a larger amount of silver nanoparticles when treated with that solution. Such is the case of *V. guatemalensis*, with the highest retention values, either by wood volume ($g_{Ag}/m^3{}_{wood}$) or by wood weight (mg_{Ag}/kg_{wood}) (Table 1). The absorption values found were similar to those reported by Taghiyari (2012) for *Fagus orientalis*, *Populus nigra*, *Platanus orientalis*, *Alnus* spp., and *Abies alba* but lower than the values given by Liu et al (2002a, 2002b, 2002c).

Decay Resistance

Adding silver nanoparticles had an effect on the protection of wood against biodeterioration by the action of *Trametes versicolor*. In untreated wood, weight losses were about 50, 35, and 25% for *A. mangium, V. guatemalensis*, and *C. odorata*, respectively. However, when silver nanoparticles were added, weight loss was less than 5% for both heartwood and sapwood of the three species. These results confirm that the effect was caused by the application of silver nanoparticles as a wood preservative.

Several studies have demonstrated the potential of silver nanoparticles for wood protection (Liu et al 2002a, 2002b, 2002c), behavior in fire (Taghiyari 2012), improvement of wood properties (Taghiyari 2012; Taghiyari and Bibalan 2013), or for already known wood treatments such as thermal treatment (Taghiyari et al 2012), wood densification (Rassam et al 2012), or particleboard manufacturing (Taghiyari et al 2011). However, the advantage of using a silver nanoparticle solution compared with a boron salts treatment (BAE) is not well quantified. A saturated solution of boric acid (H_3BO_3) and sodium borate ($Na_2B_4O_7$) at 22°C contains 94.75 g/L of H_3BO_3, whereas the system used for the synthesis of nanoparticles produces 28 mg of H_3BO_3 (Eq 1), about 1670 less times per liter than the boric acid generated for the combination of H_3BO_3 and $Na_2B_4O_7$. Similarly, the effectiveness of boric acid in terms of the BAE varies from 0.7 to 3.0 $kg/m^3{}_{wood}$ (Lloyd 1998), whereas concentration of nanoparticles varies from 13.36 to 32.66 $g_{Ag}/m^3{}_{wood}$, which is equivalent to a decrease of about 100 times of active element.

One advantage compared with traditional wood preservatives is that the silver nanoparticles at low concentrations, apart from protecting wood, can also be added in wood preservatives allowing the nondecay micro-organisms to degrade the organic preservatives (Schultz et al 2008). Likewise, the low levels of metal used may have some advantages when depositing or discarding the treated wood. However, the authors note that this type of preservative is still unprofitable.

According to ASTM D-2017 (ASTM 2003), sapwood and heartwood of the three species treated with silver nanoparticles (Fig 2) were classified as highly resistant (Class A) to attack by *T. versicolor*. Wood affected by the action of white-rot fungus, the main rot type that affects broadleaf woods, showed differences associated with treatment, type of wood, and species (Moya et al 2009; Moya and Berrocal 2010). The sapwood and heartwood of *A. mangium* without

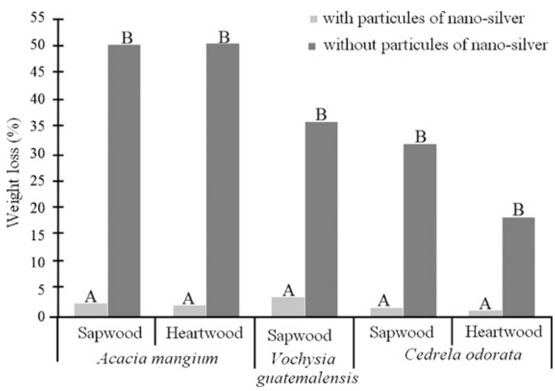


Figure 2. Weight loss caused by *Trametes versicolor* (b) on *Acacia mangium*, *Vochysia guatemalensis*, and *Cedrela odorata* wood untreated and treated with nanosilver in Costa Rica (average values identified with A and B are statistically different at $\alpha = 99\%$).

treatment was classified as resistant (Class D), whereas the sapwood of *V. guatemalensis* and *C. odorata* was classified as moderately resistant (Class C). Heartwood of *C. odorata* was considered, according to the norm, as resistant (Class B). Instead, wood treated with silver nanoparticles, regardless of the type of wood and species, was classified as highly resistant (Class A) to this type of decay.

The effect of silver nanoparticles on fungi associated with tropical species agrees with other studies. For example, Velmurugan et al (2009) found that mycelial growth of stain fungi *Ophiostoma flexuosum*, *O. tetropii*, *O. polonicum*, and *O. ips* decreased on media amended with different concentrations of silver nanoparticles synthesized from silver nitrate and sodium borohydride. They found that mycelial growth decreased with nanosilver concentration. Mycelial growth was at the highest with a concentration of 1 ppm, and the lowest growth was found with a concentration of 100 ppm. Conversely, Liu et al (2001, 2002a, 2002b, 2002c) also found a decrease of wood decay with different stabilizing agents and with addition of different fungicides to silver nanoparticle solution.

According to Dorau et al (2004), wood decay fungi have been shown to be susceptible to silver nanoparticles because the silver ions, in solution, inhibit the activity of their cellulose enzymes (Highley 1975). Wood decay fungi feeding on a block treated with silver halide would probably release more silver as a result of oxidative Fenton reactions during the breakdown of cellulose (Xu and Goodell 2001). Besides, silver nanoparticles constitute a reservoir for the antimicrobial effect. In the presence of moisture, metallic silver oxidizes, which results in the release of the silver ions. Silver ions are the species that are responsible for microbial inhibition. Because silver oxidation is a slow reaction, the size of silver particles is critical to achieve micro-organism growth inhibition. The smaller the particle size, the higher the surface area and the greater the area available for oxidation. Particles with diameters less than 100 nm are required to have the surface area necessary to allow a continuous release of silver ions. The main advantages of silver nanoparticles compared with organic biocides are that they are nonvolatile and nondegradable with time, are odorless, and have long-term efficacy (Clausen 2007).

Likewise, heat-transferring properties of silver nanoparticles are able to intensify the effect on heat treatment of wood at all temperatures. Nanosilver impregnation (400 ppm) had an intensifying effect on the results of the heat treatment against *T. versicolor* (Moradi et al 2013). Similar results were found by Reza et al (2013). They concluded that nanosilver impregnation aggravates the effects of heat treatment; however, heat treatment on nanosilver-impregnated specimens may have a greater impact on mechanical properties than physical properties. The decreasing or increasing effects of heat treatment at higher or lower temperatures on properties are also dependent on the density of the wood species.

Specific Gravity, Density, Moisture Content, Swelling and Moisture Absorption

Evaluation of wood physical properties showed that the specific gravity at 12% was only higher in the heartwood of *C. odorata* treated with silver nanoparticles (Fig 3a; Table 1). Regarding wood density, none of the species or wood types (sapwood or heartwood) were found to be significantly affected by the treatment with silver nanoparticles (Fig 3b; Table 2).

Evaluation of dimensional stability revealed a statistical decrease in swelling in the radial direction in *V. guatemalensis* and *C. odorata* (Table 2), and swelling in tangential direction also diminished in *C. odorata* (Table 2). Conversely, neither radial swelling nor tangential swelling in *A. mangium* nor tangential swelling in *V. guatemalensis* was affected statistically by the application of silver nanoparticles to the wood (Table 2). After the wood was impregnated (treated) with the nanoparticles, water absorption diminished in all three species (Table 2). Also, moisture content before the absorption test was statistically equivalent in the three species, but after the absorption test,

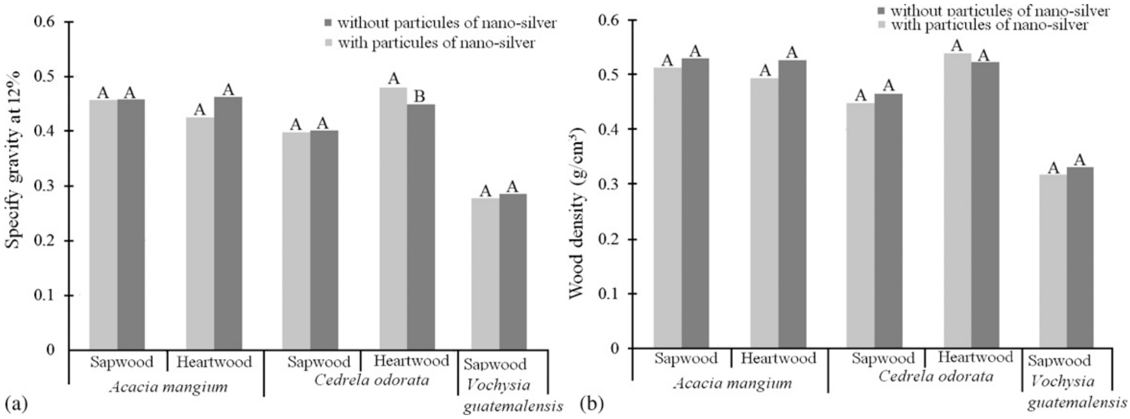


Figure 3. Comparison of specific gravity (left) and wood density (right) in wood untreated and treated with silver nanoparticles from *Acacia mangium*, *Vochysia guatemalensis*, and *Cedrela odorata* (average values identified with A and B are statistically different at $\alpha = 99\%$).

the wood treated with silver nanoparticles presented statistically lower moisture content than the untreated wood in all three species (Table 2).

The increase in specific gravity in *Cedrela odorata* can be attributed either to the amount of nanoparticles added, which in this type of wood (Table 1) was significant compared with untreated wood, or to samples of higher specific gravity being collected as specific gravity increases from pith to bark (Wiemann and Williamson 1989). For wood density of 12%, this parameter was not significantly affected by adding the nanoparticles (Fig 3b). For wood density, amount of nanoparticles added to the wood (Table 1) produced no significant increase.

The wood property most significantly affected by impregnation with nanoparticles was swelling (Tables 1 and 2). However, there appears to be no relation between absorption and swelling in radial and tangential directions because the percentage of absorption was significantly affected for all the species and for the two types of wood, whereas the swelling values were affected only for *V. guatemalensis* and *C. odorata* in the radial direction and for *C. odorata* in the tangential direction (Table 2). These results show that treatment with silver

Table 2. Swelling parameters of *Acacia mangium*, *Vochysia guatemalensis*, and *Cedrela odorata* wood untreated and treated with silver nanoparticles.[a]

Wood properties	Treatment	*Acacia mangium*	*Vochysia guatemalensis*	*Cedrela odorata*	Average
Radial swelling (%)	With nanosilver	2.92^{A} (20)	3.68^{A} (11)	1.42^{A} (22)	3.13 (29)
	Without nanosilver	3.08^{A} (23)	4.12^{B} (18)	2.36^{B} (20)	2.73 (41)
Tangential swelling (%)	With nanosilver	1.00^{A} (32)	1.38^{A} (43)	0.98^{A} (16)	1.43 (40)
	Without nanosilver	1.02^{A} (37)	1.27^{A} (50)	1.92^{B} (17)	1.09 (41)
Moisture content before nanosilver treated (%)	With nanosilver	12.95^{A} (6)	14.95^{A} (7)	14.11^{A} (3)	14.00 (8)
	Without nanosilver	12.47^{A} (9)	14.45^{A} (7)	15.11^{A} (2)	15.34 (15)
Moisture content after nanosilver treated (%)	With nanosilver	74.63^{A} (9)	148.17^{A} (8)	45.65^{A} (6)	89.48 (49)
	Without nanosilver	67.28^{B} (10)	125.15^{B} (10)	40.34^{B} (7)	77.59 (47)
Water absorption	With nanosilver	54.60^{A} (10)	115.92^{A} (9)	27.65^{A} (9)	66.06 (57)
	Without nanosilver	48.71^{B} (12)	93.30^{B} (10)	19.84^{B} (12)	53.95 (58)

[a] Values in parentheses show coefficient of variation. Average values identified with A and B are statistically different at $\alpha = 99\%$.

nanoparticles decreased the absorption of water in the various tropical species but that water absorbed to some species such as *A. mangium* had no effect in increasing the dimensional stability. The cell wall of the timber reveals porosity on a molecular level because of the partial arrangement of the cellulose microfibrils and because of the partial filling of these spaces by lignin, hemicellulose, and extractives (Wegner and Jones 2006). Very small-sized nanoparticles can penetrate the pores, preventing moisture from entering and thus decreasing water absorption (Mantanis and Papadopoulos 2010a), as occurred in all the species studied (Table 2). Nevertheless, dimensional stability was different for each species, probably because of the nature of the extractives in *A. mangium*, which does not allow nanoparticles to join the OH cellulose and hemicellulose groups (Mantanis and Papadopoulos 2010b). Hygroscopicity decreased in the treated wood because the adsorbed water was separated into hydrate water relating to monomolecular sorption and dissolved water relating to polymolecular sorption (Mantanis and Papadopoulos 2010b).

CONCLUSIONS

Dimensions of the synthetized silver nanoparticles ranged from 10 to 25 nm with few clusters and a good distribution in the solution. Retentions of 25-102 silver mg were achieved, depending on the species and the presence of sapwood and heartwood. This level of nanoparticle retention is approximately 1670 times less than the retention of the wood when preserved with a combination of boric acid and sodium borate.

Silver nanoparticles applied to the tropical species studied here improved durability of the wood of those species. For all cases, the nanoparticle-treated woods were classified as highly resistant or Class A for white (*Trametes versicolor*) decay fungi, as opposed to untreated wood, whose weight losses were more than 20%. Also, in addition to improved resistance to fungal attack, water absorption capacity of wood from the three species tested decreased with silver nanoparticles and dimensional stability increased in *Cedrela odorata* and *Vochysia guatemalensis*.

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