Influence of Nanosilica on the Vibro-acoustic Behavior and Morphological Characteristics of Wood Flour/ Recycled Polystyrene Composites

Majid Kiaei [a,*] and Maryam Veylaki [b]

This study investigated the influence of nanosilica on the vibro-acoustic behavior, microstructure, and structural characteristics of composites based on poplar wood flour and recycled polystyrene. Composites containing 50 wt% wood flour and 0, 2, 4, and 6 phc nanosilica were prepared using twin-screw extrusion. Vibro-acoustic properties were evaluated using a non-destructive flexural vibration method, while the fractured-surface morphology and diffraction characteristics were examined by scanning electron microscopy (SEM) and X-ray diffraction (XRD), respectively. Nanosilica caused only minor changes in sound velocity, loss tangent, acoustic coefficient, acoustic conversion efficiency, and dynamic modulus of elasticity, with no statistically significant differences among the formulations ($p > 0.05$). SEM images showed apparent reductions in interfacial voids and improved contact between the wood flour and polymer matrix with nanosilica incorporation. XRD patterns indicated that the composites retained a predominantly amorphous character, while the changes in diffraction intensity suggested differences in X-ray scattering following nanosilica incorporation. Overall, nanosilica altered the apparent microstructural characteristics of the composites without significantly affecting their vibro-acoustic performance. The combination of stable vibro-acoustic properties and the use of recycled polystyrene suggests potential for these composites in lightweight panel and interior applications where stable acoustic behavior is desirable.

DOI: 10.15376/biores.21.4.10232-10245

Keywords: Nanosilica; Recycled polystyrene; Wood flour; Wood–plastic composite; Vibro-acoustic properties; Scanning electron microscopy (SEM); X-ray diffraction (XRD)

*Contact information: a: Department of Wood and Paper Science and Technology, Cha.C., Islamic Azad University, Chalus, Iran; b: Department of Basic Sciences, Cha.C., Islamic Azad University, Chalus, Iran; * Corresponding author: mjd_kia59@iau.ac.ir*

INTRODUCTION

The rapid growth in the production and consumption of polymeric materials during recent decades has led to a significant increase in the generation of plastic waste worldwide (Geyer *et al.* 2017). Among synthetic polymers, polystyrene is widely used due to its low density, relatively low cost, and good processability. It is extensively applied in packaging materials, household appliances, construction products, and disposable items (Andrady and Neal 2009). However, the persistence of this polymer in the environment and the accumulation of large quantities of plastic waste have raised serious environmental concerns (Hopewell *et al.* 2009). Therefore, recycling and reprocessing of polystyrene for the production of new engineering materials have been considered an effective strategy to

reduce environmental impacts while increasing the added value of polymer resources (Ragaert *et al.* 2017).

Wood–plastic composites (WPCs) have attracted considerable attention in recent years because they combine the advantages of lignocellulosic materials with those of thermoplastic polymers (Faruk *et al.* 2012). These composites are typically produced by mixing wood flour or natural fibers with thermoplastic matrices such as polyethylene, polypropylene, or polystyrene (Clemons 2002). Because of their relatively low density, favorable processability**,** acceptable moisture resistance, and competitive production cost, WPCs have found widespread applications in building materials, interior decoration, flooring, wall panels, and various structural components (Ashori 2008). Furthermore, the use of recycled polymers in WPC production contributes to the sustainable management of plastic materials and reduces the environmental burden associated with plastic waste (Klyosov 2007).

Despite their advantages, wood–plastic composites may still exhibit certain limitations, such as moderate mechanical strength, limited thermal stability, and relatively high flammability, compared with some conventional engineering materials (Faruk *et al.* 2012). To overcome these limitations and improve the overall performance of WPCs, the incorporation of nanoparticles as reinforcing fillers has attracted increasing attention **(**Ray and Okamoto 2003**).** Among various nanofillers, nanosilica has attracted considerable attention because of its high specific surface area, good thermal stability, relatively low cost, and potential to enhance interfacial interactions within polymer composites (Ray and Okamoto 2003). Previous studies have shown that the addition of nanosilica can improve several properties of WPCs, including mechanical strength, thermal stability, and fire resistance (Deka and Maji 2012; Kiaei *et al.* 2018; Amini *et al.* 2023).

In addition to mechanical and thermal performance, the acoustic behavior of engineering materials has become an important consideration, particularly for materials used in construction and interior applications (Bucur 2006). With the increasing use of WPCs in interior panels, partition walls, and decorative elements, properties related to sound propagation and vibration damping have gained greater attention in evaluating the performance of WPCs. Recent studies have demonstrated the importance of vibro-acoustic characterization of wood-based composite panels and have shown that the structural and mechanical characteristics of WPCs can influence their acoustic and vibration behavior (Santoni *et al.* 2020). The propagation of sound waves in solid materials is strongly influenced by several parameters, including density, elastic modulus, internal damping, porosity, and structural homogeneity (Bucur 2006). Moreover, the quality of the interface between different phases in composite materials plays a significant role in determining the transmission and attenuation of sound waves (Obataya *et al.* 2000). Recent research has also indicated that acoustic and wave-propagation measurements can be used to characterize the stiffness and strength of wood-polymer composites, with wave velocity being affected by composite formulation and wood-filler content (Hillig *et al.* 2024). Therefore, any modification in the internal structure of a composite material may influence its acoustic characteristics.

Previous studies have mainly focused on the influence of nanoparticles on the mechanical, thermal, and physical properties of wood–plastic composites. For instance, Ashori and Nourbakhsh (2009) reported that the incorporation of nanoparticles improved several physical and mechanical properties of lignocellulosic composites. Faruk *et al.* (2012) also highlighted the important role of nanofillers in enhancing the overall

performance of bio-based composites. In addition, Kord and Tajik (2014) investigated the effect of nanoclay on the acoustic properties of wood flour/polypropylene composites and reported that increasing nanoclay content increased sound propagation time and acoustic energy absorption while decreasing sound propagation velocity. Their results also showed that the addition of 3 phc nanoclay significantly improved the tensile modulus of the composites. Structural analyses using X-ray diffraction (XRD) and transmission electron microscopy (TEM) confirmed the formation of an intercalated nanostructure within the polymer matrix.

Although several studies have investigated the influence of nanoparticles on the performance of wood–plastic composites, limited information is available regarding the effect of nanosilica on the vibro-acoustic properties of wood flour/polystyrene nanocomposites. Understanding these effects is important because the incorporation of nanosilica can modify the microstructure of the composite and may affect stress distribution, particle dispersion, and internal porosity, thereby potentially influencing the dynamic behavior of the material.

Accordingly, the present study investigated the effect of different nanosilica contents on the vibro-acoustic properties and morphological characteristics of composites based on wood flour and recycled polystyrene. Acoustic parameters including sound propagation velocity, acoustic coefficient, and acoustic conversion efficiency were evaluated. In addition, scanning electron microscopy (SEM) and XRD analyses were performed to examine the microstructural characteristics of the composites and to better understand the relationship between their structural features and acoustic behavior.

EXPERIMENTAL

Materials

Poplar wood flour (WF) was used as the lignocellulosic reinforcement in the composite system. The material was supplied by Cellulose Aria Co. (Iran). To obtain a uniform particle size distribution, the poplar wood flour was sieved using a vibratory sieve shaker. The fraction passing through a 60-mesh sieve and retained on an 80-mesh sieve was selected for the experiments. Prior to composite preparation, the wood flour particles were oven-dried at 100 ± 3 °C for 24 h to remove moisture and prevent void formation during processing.

Recycled polystyrene (RPS) was used as the polymer matrix. The polystyrene was initially obtained in commercial granulated form from Tabriz Petrochemical Company (Tabriz, Iran), with a density of 1.07 g/cm³ and a melt flow index (MFI) of 18 g/10 min. Prior to composite preparation, the polystyrene granules were processed twice through an extruder at a temperature of 180 °C and a screw speed of 100 rpm. After extrusion, the material was cooled and ground into granules using a milling device. The resulting reprocessed polystyrene was subsequently used as the polymer matrix and is referred to as recycled polystyrene (RPS) throughout this study.

Maleic anhydride-grafted polypropylene (MAPP) was used as a compatibilizing agent to improve the interfacial interaction between the hydrophilic wood flour and the hydrophobic polymer matrix. The MAPP was supplied by Kimia Javid Co. (Iran) and had a melt flow index of 11 g/10 min with 1.1 wt% grafted maleic anhydride.

Nanosilica (NS) powder was used as a nanofiller to investigate its effect on the structural and vibro-acoustic properties of the composites. The nanosilica was produced by Degussa Co. (Germany). The main characteristics of the nanosilica used in this study are summarized in Table 1.

Table 1. Main Characteristics of Nanosilica Used in This Study

Silicon Oxide	SiO_2
Silicon oxide (SiO_2) purity	99+%
Average particle size (APS)	11-13 nm
Specific surface area (SSA)	200 $m^2 g^{-1}$
True density	2.4 $g\ cm^{-3}$
Bulk density	<0.10 $g\ cm^{-3}$
Color	White
Moisture	<2%
Weight loss on ignition	30%
Ti	< 120 ppm
Ca	< 70 ppm
Na	< 50 ppm
Fe	< 20 ppm

Note: According to the producer's information

Methods

Preparation of composites

Hybrid wood flour/polystyrene composites were prepared to evaluate the influence of nanosilica content on the vibro-acoustic performance of the material. Poplar wood flour was used at a constant content of 50 wt% based on the total composite weight, while the polymer matrix consisted of 50 wt% recycled polystyrene (RPS). The coupling agent (MAPP) was added at a fixed level of 3 phc (parts per hundred composite), where phc was calculated based on the total mass of the wood flour/recycled polystyrene composite. Nanosilica was incorporated at 0, 2, 4, and 6 phc, with the phc values likewise calculated relative to the total mass of the wood flour/recycled polystyrene composite.

Before processing, the required amounts of wood flour, recycled polystyrene granules, nanosilica powder, and coupling agent were accurately weighed according to the formulations presented in Table 2. The components were first premixed manually to obtain a relatively homogeneous mixture and to promote uniform distribution of the nanosilica within the composite system. The premixed materials were then compounded using a twin-screw extruder (Dr. Collin GmbH, Germany). The compounding process was performed at a processing temperature of 160 °C and a screw rotation speed of 70 rpm. During extrusion, the materials were melted, mixed, and homogenized to produce a uniform composite melt.

Table 2. Formulation of the Prepared Composites

No	Code	WF(%)	RPS (%)	NS (phc)	MAPP (phc)
1	50WF50RPS0NS	50	50	0	3
2	50WF50RPS2NS	50	50	2	3
3	50WF50RPS4NS	50	50	4	3
4	50WF50RPS6NS	50	50	6	3
Note: WF = poplar wood flour; RPS = recycled polystyrene; NS = nanosilica; MAPP = maleic anhydride-grafted polypropylene; phc = parts per hundred composite					

Specimen preparation

After the compounding stage, the extrudates were cooled to room temperature and pelletized using a semi-industrial grinder (Wieser WG-Ls 200, Germany). The obtained granules were subsequently dried in an oven at 65 °C for 24 h to remove residual moisture prior to specimen fabrication.

Test specimens were produced using a laboratory hot press machine (Toyoseiki, Japan). The composite granules were placed in a steel mold and pressed at a temperature of 200 °C for 4 min under a pressure of 25 MPa. Composite boards with dimensions of 220 × 50mm and a thickness of 10 mm were prepared using the hot-pressing process. After the pressing stage, the molded boards were cooled to approximately 80 °C while maintaining the applied pressure to prevent internal stresses and warping. For the acoustic tests, specimens with dimensions of 200 × 50 × 10 mm were prepared.

Vibro-acoustic measurements

The vibro-acoustic properties of the composites were evaluated using a non-destructive flexural vibration method in accordance with ASTM C1548 (2016). Although ASTM C1548 was originally developed for refractory materials, its impulse-excitation/flexural vibration approach has also been adapted for wood-based materials. For example, Roohnia and Kohantorabi (2015) fitted the ASTM C1548 methodology to wood and demonstrated that the dynamic vibration approach could provide results comparable to other established torsional and flexural vibration methods. In the present study, the impulse-excitation/flexural vibration procedure described in ASTM C1548 was therefore used as a methodological framework for determining the dynamic response of the wood flour/recycled polystyrene composites. The standard was used as a reference for the vibration measurement procedure and not as a material-specific qualification standard. Rectangular specimens with uniform geometry and smooth surfaces were prepared from the pressed boards. Before testing, all specimens were conditioned at a temperature of 23 ± 2 °C and a relative humidity of 50 ± 5 % for at least 48 h to ensure moisture equilibrium.

During the test, each specimen was positioned horizontally on two elastic supports located at approximately 0.224 × L from each end, where L is the specimen length, corresponding to the nodal points of the first flexural vibration mode. This configuration minimizes external damping effects and allows free flexural vibration conditions.

The specimen was excited by a light mechanical impulse applied at one end using a small hammer. The vibration response was measured using a laboratory-developed free flexural vibration testing system based on the NDT-Lab® software (version 4.01; CIRAD, France), which was adapted and localized for laboratory use. The vibration signal was captured by a sensitive microphone positioned near the opposite end of the specimen and transferred to a computer for signal processing. The fundamental flexural resonant frequency (f_1) was determined from the recorded frequency spectrum using Fast Fourier Transform (FFT) analysis.

Based on the measured resonant frequency, specimen dimensions, and density (ρ), the dynamic modulus of elasticity (E') was calculated according to the flexural vibration theory. The sound velocity (v) in the material was determined using the following relationship:

$$v = \sqrt{(E' / \rho)} \quad (1)$$

The internal damping behavior of the material was evaluated by calculating the loss tangent (tanδ) from the decay of vibration amplitude. In addition, the acoustic coefficient (AC) and acoustic conversion efficiency (ACE) were determined using standard relationships involving sound velocity, density, and damping parameters. For each formulation, three replicate specimens (n = 3) were tested, and the average values were reported.

X-ray diffraction analysis

The XRD analysis was conducted to characterize the diffraction patterns and structural features of the composite materials and to assess changes associated with nanosilica incorporation. The analysis was performed using an X-ray diffractometer (X'Pert, Philips, Netherlands). The measurements were carried out using cobalt radiation with a wavelength of 1.789 Å. The scanning parameters included a step size of 0.02°, a scanning speed of 0.3° s^{-1}, and a diffraction angle range of 1° to 9°. The relatively narrow 2θ range of 1° to 9° was selected to focus on the low-angle diffraction features of the composite materials and to compare changes in the broad diffraction halo associated with nanosilica incorporation. Because the XRD measurements were limited to this range, the analysis was used only to assess changes in diffraction intensity and the overall amorphous character of the composites, rather than to make broader conclusions regarding crystallinity, molecular packing, or structural ordering. The generator voltage and current were set to 40 kV and 30 mA, respectively.

Morphological analysis

The morphology of the fractured surfaces of the composites was examined using SEM (AIS2100, Gyeonggi, South Korea). Prior to observation, the specimens were immersed in liquid nitrogen and fractured to obtain clean and representative fracture surfaces. The samples were then sputter-coated with a thin layer of gold to provide electrical conductivity during SEM observation.

Statistical Analysis

The experimental data were analyzed using one-way analysis of variance (ANOVA) to evaluate the influence of nanosilica content (0, 2, 4, and 6 phc) on the vibro-acoustic properties of the prepared composites. Prior to performing the ANOVA, the assumption of homogeneity of variances was assessed using Levene's test. When significant differences were detected in the ANOVA results, Duncan's multiple range test was applied to compare the mean values at a 95% confidence level.

RESULTS AND DISCUSSION

Vibro-acoustic Properties

The vibro-acoustic properties of recycled polystyrene/wood flour composites containing different nanosilica loadings are presented in Table 3. The evaluated parameters include the tanδ, AC, ACE, v, and E'. The results of one-way ANOVA indicated that the incorporation of nanosilica within the studied range did not have a statistically significant effect on the measured acoustic parameters ($p > 0.05$).

Table 3. Descriptive Statistics (Mean ± Standard Deviation) of the Acoustic Properties of the Prepared Composites

Nanosilica (phc)	Tanδ	AC (m^4/kg.s)	ACE (m^4/kg.s)	Sound Velocity (m/s)	E′ (GPa)
0	0.0156 (0.0019)	1.7759 (0.0034)	114.84 (13.57)	2009.8 (20.8)	4.57 (0.13)
2	0.0195 (0.0055)	1.7819 (0.0127)	98.15 (14.06)	2038.8 (18.5)	4.76 (0.14)
4	0.0132 (0.0007)	1.7807 (0.0101)	134.79 (7.69)	2025.8 (53.9)	4.67 (0.36)
6	0.0154 (0.0012)	1.7668 (0.0226)	115.23 (10.43)	2010.3 (20.4)	4.66 (0.16)
F	2.01	0.78	1.74	0.56	0.36
p-value	0.191	0.539	0.235	0.654	0.785

The loss tangent (tanδ), which represents the damping capacity of a material and its ability to dissipate vibrational energy, ranged from 0.0132 to 0.0195. The highest value was observed for the composite containing 2 phc nanosilica (0.0195), suggesting a slight increase in internal damping. However, the ANOVA results indicated that this variation was not statistically significant ($F = 2.01$, $p = 0.191$). The observed fluctuations may be associated with minor changes in the microstructural arrangement of the composite and the increase in internal friction caused by nanosilica particles. Similar behavior has been reported in wood-based and polymer composite systems containing nanoscale fillers (Obataya *et al.* 2000; Bucur 2006; Hillig *et al.* 2018).

The AC exhibited only a narrow range of variation, with values between 1.7668 and 1.7819 m^4/kg.s. The highest value was recorded for the composite containing 2 phc nanosilica, whereas the lowest value was observed for the composite containing 6 phc nanosilica. Statistical analysis confirmed that these differences were not significant ($F = 0.78$, $p = 0.539$). Because the acoustic coefficient depends primarily on sound velocity and density, the relative stability of this parameter indicates that the addition of nanosilica within the studied range did not significantly alter the effective density or structural integrity of the composite.

The ACE, which reflects the efficiency of mechanical vibration transfer into acoustic radiation, showed relatively larger numerical variation compared to AC. The highest ACE value was obtained for the composite containing 4 phc nanosilica (135 m^4/kg.s), whereas the lowest value was observed for the composite containing 2 phc nanosilica (98.2 m^4/kg. s). Nevertheless, ANOVA results revealed that these differences were not statistically significant ($F = 1.74$, $p = 0.235$). The relatively higher numerical ACE value at 4 phc nanosilica should be interpreted cautiously because the difference among the formulations was not statistically significant ($p = 0.235$), and the present study did not provide direct quantitative evidence of nanosilica dispersion.

Sound velocity in solid materials is strongly dependent on elastic modulus, density, and internal structural continuity (Bucur 2006). In wood–plastic composites, improved interfacial bonding between wood particles and the polymer matrix can enhance stress transfer and facilitate wave propagation (Faruk *et al.* 2012). In the present study, sound velocity ranged from 2009 to 2039 m/s. The highest value was observed for the composite containing 2 phc nanosilica (2038.8 m/s), whereas the control sample exhibited a value of 2009.8 m/s. Despite this slight increase, statistical analysis revealed no significant

difference among the treatments ($F = 0.56$, $p = 0.654$). The limited variation suggests that nanosilica incorporation did not substantially modify the effective stiffness or density of the composite.

A similar trend was observed for the dynamic modulus of elasticity (E'), which ranged from 4.57 to 4.76 GPa. The maximum value was obtained for the composite containing 2 phc nanosilica (4.76 GPa), while the control sample showed a value of 4.57 GPa. However, ANOVA results confirmed that these differences were not statistically significant ($F = 0.36$, $p = 0.785$). This indicates that the addition of nanosilica at the studied concentrations did not significantly influence the dynamic stiffness of the composite system.

Overall, the results demonstrate that nanosilica incorporation caused only minor variations in the vibro-acoustic behavior of recycled polystyrene/wood flour composites. These variations were not statistically significant, suggesting that the acoustic response of the composite is mainly governed by the bulk viscoelastic properties of the polymer matrix and the overall composite structure rather than by the relatively small fraction of nanosilica.

Scanning Electron Microscopy

Scanning electron microscopy images of the fractured surfaces of recycled polystyrene/wood flour composites with different nanosilica contents are presented in Fig. 1. The control sample exhibited relatively large and deep voids within the matrix. These voids may be associated with the pull-out of wood flour particles from the polystyrene matrix, suggesting relatively weak interfacial adhesion and limited compatibility between the lignocellulosic filler and the polymer matrix. Such defects may act as stress concentration sites and influence the propagation and dissipation of vibrational energy within the composite.

With the incorporation of nanosilica at 2 and 4 phc, the size and apparent frequency of interfacial voids appeared to decrease. As indicated by the arrows in the micrographs, the interfacial gaps between the wood flour particles and the polymer matrix appeared narrower or partially filled, resulting in a visually more compact fracture morphology. This suggests that nanosilica incorporation may have contributed to improved interfacial interaction between the wood flour and the recycled polystyrene matrix.

At 6 phc nanosilica, the wood particles appeared to be more uniformly embedded within the polymer matrix. The boundary between the wood particles and the matrix appeared less distinct, which may indicate improved matrix–filler contact. The formation of a more continuous microstructure with fewer apparent interfacial defects may contribute to the observed morphological integrity of the composite.

These microstructural observations are consistent with the acoustic measurements, in which only slight variations were observed in parameters such as $\tan\delta$, acoustic coefficient, acoustic conversion efficiency, sound velocity, and dynamic modulus of elasticity. Although the statistical analysis indicated no significant differences among the treatments, the SEM results suggest that nanosilica incorporation was associated with a more compact fracture morphology and fewer apparent interfacial voids. However, because the SEM observations were qualitative and the voids were not quantitatively measured, the extent of void reduction and interfacial improvement cannot be considered statistically significant. Furthermore, the absence of statistically significant differences in the vibro-acoustic parameters indicates that the observed morphological changes did not result in measurable changes in the tested acoustic properties.

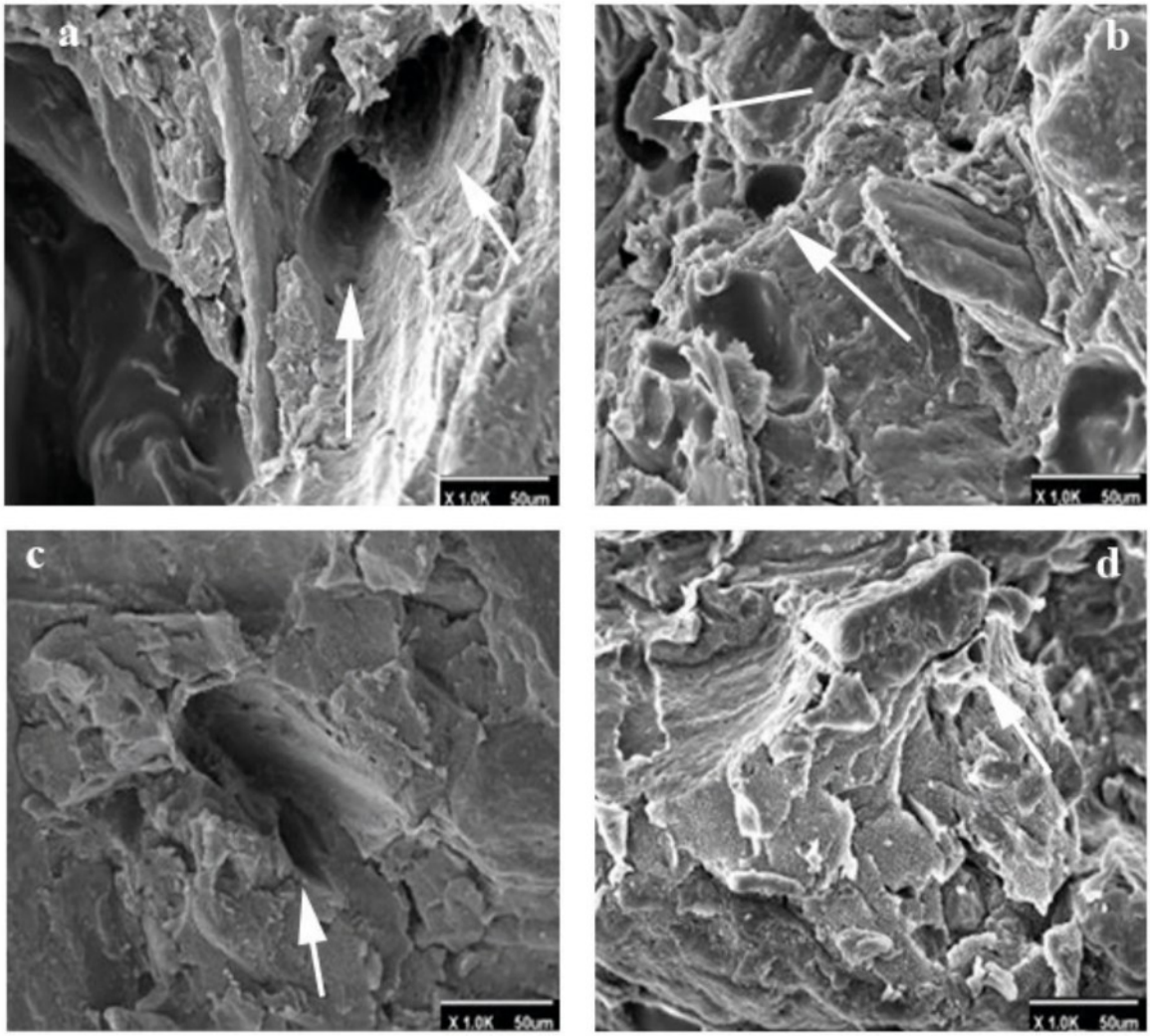

Fig. 1. SEM images of the fractured surfaces of the samples obtained at the same magnification (10,000×): (a) control sample without nanosilica, (b) 2 phc nanosilica, (c) 4 phc nanosilica, and (d) 6 phc nanosilica. The arrows indicate apparent interfacial voids associated with wood particle pull-out. The scale bar represents 50 μm.

XRD

Figure 2 illustrates the X-ray diffraction patterns of the control composite (50% wood flour/50% recycled PS) and the composites reinforced with 2, 4, and 6 phc of nanosilica. The control sample (yellow line) exhibited a broad and low-intensity diffraction halo, which is consistent with a predominantly amorphous character within the measured 2θ range. Upon the incorporation of nanosilica, an increase in diffraction intensity was observed. However, because the XRD measurements were limited to the 1° to 9° range, these intensity changes should be interpreted cautiously and primarily as differences in the observed scattering response rather than as direct evidence of changes in crystallinity, structural density, or molecular packing. While the patterns did not exhibit sharp crystalline peaks within the measured range, the overall broad nature of the diffraction features suggests that no pronounced crystalline features were detected in this range.

The increase in diffraction intensity may be related to the presence of nanosilica particles and their contribution to the overall X-ray scattering response of the composite. However, the present XRD data do not allow a definitive assessment of nanosilica dispersion or molecular packing. The similarity in the peak positions for the 2, 4, and 6 phc samples suggests that no major changes in the observed diffraction features occurred with increasing nanosilica content. Given the limited scanning range, these observations are considered indicative of changes in the diffraction response rather than definitive evidence of increased structural order. Similar observations regarding the preservation of the predominantly amorphous character of wood-polymer composites have been reported by Deka and Maji (2012).

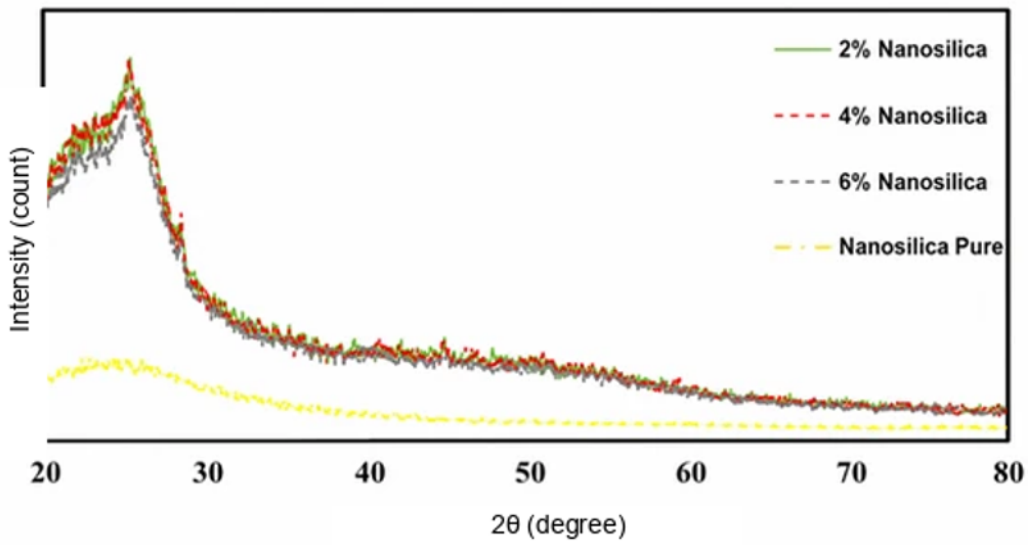

Fig. 2. XRD patterns of composites made from 50% wood flour containing 2, 4, and 6 phc nanosilica, as well as pure nanosilica (control sample)

Relationship between SEM, XRD, and Acoustic Properties

The integrated analysis of SEM, XRD, and vibro-acoustic data provides complementary information on the morphology, diffraction response, and acoustic behavior of the composites.

The SEM observations demonstrated that increasing the nanosilica content was associated with a more compact fracture morphology and fewer apparent interfacial gaps. These observations suggest improved contact between the wood flour and the recycled polystyrene matrix; however, the SEM analysis was qualitative, and the extent of interfacial void reduction was not quantitatively evaluated.

The XRD results showed that the composites exhibited predominantly broad diffraction features within the measured 2θ range of 1° to 9°. The observed increase in diffraction intensity with nanosilica incorporation may reflect changes in the overall X-ray scattering response of the composites. However, because of the limited scanning range, the XRD results cannot be used to make definitive conclusions regarding nanosilica dispersion, molecular packing, or increased structural order**.**

The slight, non-significant variations in acoustic damping ($\tan\delta$) may reflect the combined effects of interfacial interactions and the presence of nanosilica within the composite matrix. However, these possible mechanisms cannot be directly confirmed from

the present measurements. The absence of statistically significant differences in tanδ, AC, ACE, sound velocity, and dynamic modulus of elasticity indicates that the incorporation of nanosilica at the studied levels did not produce measurable changes in the overall vibro-acoustic response of the composites.

Overall, the SEM observations indicate changes in fracture morphology associated with nanosilica incorporation, whereas the XRD results indicate changes in the observed diffraction response within the limited scanning range. These morphological and diffraction changes were not accompanied by statistically significant changes in the measured vibro-acoustic properties. Therefore, the acoustic behavior of the composites appears to remain primarily governed by their bulk composition and viscoelastic characteristics.

CONCLUSIONS

This study investigated the influence of nanosilica incorporation on the vibro-acoustic behavior, microstructure, and diffraction characteristics of recycled polystyrene/poplar wood flour composites. Based on the experimental results, the following conclusions can be drawn:

1. The addition of nanosilica at levels of 2 to 6 phc did not significantly affect the measured vibro-acoustic parameters, including tanδ, acoustic coefficient (AC), acoustic conversion efficiency (ACE), sound velocity, and dynamic modulus of elasticity (E', $p > 0.05$). The observed numerical variations were relatively small and were not statistically significant.

2. Although the composite containing 2 phc nanosilica showed the highest numerical values of sound velocity and dynamic modulus of elasticity, and the 4 phc formulation showed the highest numerical ACE value, these differences were not statistically significant. Therefore, these numerical differences should not be interpreted as evidence of a beneficial effect of a specific nanosilica content on the vibro-acoustic properties.

3. The SEM observations showed morphological differences among the formulations, with fewer apparent interfacial gaps and a more compact fracture morphology observed in the nanosilica-containing composites. These observations suggest improved contact between the wood flour and recycled polystyrene matrix; however, the SEM analysis was qualitative and the extent of void reduction was not quantitatively evaluated.

4. The XRD patterns exhibited predominantly broad diffraction features within the measured 2θ range of 1° to 9°. The observed changes in diffraction intensity following nanosilica incorporation indicate differences in the X-ray scattering response; however, because of the limited scanning range, the XRD results do not provide sufficient evidence to draw definitive conclusions regarding crystallinity, molecular packing, nanosilica dispersion, or structural ordering.

5. Overall, nanosilica incorporation produced observable changes in the fracture morphology and diffraction response of the composites, while no statistically significant changes were detected in the measured vibro-acoustic properties. The results therefore indicate that nanosilica can be incorporated at the studied levels without significantly altering the evaluated vibro-acoustic performance of the recycled polystyrene/wood flour composites.

ACKNOWLEDGMENTS

The authors would like to express their sincere gratitude to Cha. C, Islamic Azad University, Iran, for supporting this research study.

Conflict of Interest

The authors declare that there are no conflicts of interest that could have influenced the research or publication of this manuscript.

Use of Generative AI

The authors used ChatGPT (OpenAI, USA) solely for English language editing. The content, data, and scientific interpretation were fully produced and verified by the authors.

REFERENCES CITED

Amini, A., Farsi, M., Ebadi, M., Maashi Sani, F., and Shahbabaei, M. (2023). "Effect of microwave heat treatment on physical and mechanical properties of high-density polyethylene/wood flour/nano-SiO_2 composites," *Journal of Thermoplastic Composite Materials* 36(8), 3312-3331. https://doi.org/10.1177/08927057221128186

Andrady, A. L., and Neal, M. A. (2009). "Applications and societal benefits of plastics," *Philos. Trans. R. Soc. B* 364(1526), 1977-1984. https://doi.org/10.1098/rstb.2008.0304

Ashori, A. (2008). "Wood plastic composites as promising green composites for automotive industries," *Bioresource Technol.* 99(11), 4661-4667. https://doi.org/10.1016/j.biortech.2007.09.015

Ashori, A., and Nourbakhsh, A. (2009). "Effects of nanoclay as a reinforcement filler on the physical and mechanical properties of wood-based composite," *J. Compos. Mater.* 43(18), 1869-1875 . https://doi.org/10.1177/0021998309340936

ASTM International. (2016). ASTM C1548-16, "Standard test method for dynamic Young's modulus, shear modulus, and Poisson's ratio of refractory materials by impulse excitation of vibration," ASTM International, West Conshohocken, PA, USA.

Brémaud, I. (2012). "Acoustical properties of wood in string instruments soundboards: Biological and cultural diversity," *Acta Acust. United Ac.* 98(6), 857-863. https://doi.org/10.3813/AAA.918569

Bucur, V. (2006). *Acoustics of Wood*, Springer, Berlin, Germany. https://doi.org/10.1007/1-4020-3822-8

Clemons, C. M. (2002). "Wood plastic composites in the United States: The interfacing of two industries," *Forest Prod. J.* 52(6), 10-18. https://doi.org/10.13073/0015-7473-52.6.10

Deka, B. K., and Maji, T. K. (2012). "Effect of SiO_2 and nanoclay on the properties of wood polymer nanocomposite," *Polym. Bull*. 70(2), 403-417. https://doi.org/10.1007/s00289-012-0814-5

Faruk, O., Bledzki, A. K., Fink, H. P., and Sain, M. (2012). "Biocomposites reinforced with natural fibers: 2000–2010," *Prog. Polym. Sci.* 37(11), 1552-1596. https://doi.org/10.1016/j.progpolymsci.2012.04.003

Geyer, R., Jambeck, J. R., and Law, K. L. (2017). "Production, use, and fate of all plastics ever made," *Sci. Adv.* 3(7), article e1700782. https://doi.org/10.1126/sciadv.1700782

Hillig, É., Bobadilla, I., Arriaga, F., and Íñiguez-González, G. (2024). "Using acoustic testing to estimate strength and stiffness of wood-polymer composites," *Maderas. Ciencia y Tecnología* 26 (1), 1-16. https://doi.org/10.22320/S0718221X/2024.04

Hillig, É., Bobadilla, I., Gonçalves, R., and Llana, D. F. (2018). "The influence of wood polymer composite (WPC) specimen composition and dimensions on wave propagation," *Eur. J. Wood Wood Prod.* 76(4), 1033-1042. https://doi.org/10.1007/s00107-018-1309-9

Hopewell, J., Dvorak, R., and Kosior, E. (2009). "Plastics recycling: Challenges and opportunities," *Philos. T. R. Soc. B.* 364(1526), 2115-2126. https://doi.org/10.1098/rstb.2008.0311

Kiaei, M., Amiri, H., Samariha, A., and Amani, N. (2018). "Effect of nanosilica on thermal, flammability, and morphological properties of WF/rPS based nanocomposites," *Cerne* 24(1), 59-66. https://doi.org/10.1590/01047760201824012493

Kord, B., and Tajik, M. (2014). "Effect of organomodified montmorillonite on acoustic properties of wood–plastic nanocomposites," *J. Thermoplast. Compos. Mater.* 27(6), 731-740. https://doi.org/10.1177/0892705712454864

Klyosov, A. A. (2007). *Wood-Plastic Composites*, Wiley, Hoboken, NJ, USA. https://doi.org/10.1002/9780470165935

Obataya, E., Ono, T., and Norimoto, M. (2000). "Vibrational properties of wood along the grain," *J. Mater. Sci.* 35(12), 2993-3001. https://doi.org/10.1023/A:1004782827844

Ragaert, K., Delva, L., and Van Geem, K. (2017). "Mechanical and chemical recycling of solid plastic waste," *Waste Manage.* 69, 24-58. https://doi.org/10.1016/j.wasman.2017.07.044

Ray, S. S., and Okamoto, M. (2003). "Polymer/layered silicate nanocomposites: A review from preparation to processing," *Prog. Polym. Sci.* 28(11), 1539-1641. https://doi.org/10.1016/j.progpolymsci.2003.08.002

Roohnia, M., and Kohantorabi, M. (2015). "Dynamic methods to evaluate the shear modulus of wood," *BioResources* 10(3), 4867-4876. https://doi.org/10.15376/biores.10.3.4867-4876

Santoni, A., Bonfiglio, P., Fausti, P., Marescotti, C., Mazzanti, V., and Pompoli, F. (2020). "Characterization and vibro-acoustic modeling of wood composite panels," *Materials* 13(8), article 1897. https://doi.org/10.3390/ma13081897

Article submitted June 22, 2026; Peer review completed: August 15, 2026; Revised version received and accepted: August 17, 2026; Published: September 1, 2026.
DOI: 10.15376/biores.21.4.10232-10245