SciEn

Proceedings of 8th International Conference on Mechanical Engineering and Renewable Energy 2025
10-12 December, 2025, Chattogram, BANGLADESH

SciEn Conference Series: Engineering Vol. 4, 2026, pp 129-135 https://doi.org/10.38032/scse.2026.4.63

A Comparative Analysis among Balsa, Pine, and Gamari as a Potential Piezoelectric Material

Abu Bakkar[1,], Chinmoy Deb Nath[1] , Sajal Chandra Banik[2]*

[1]Department of Mechanical Engineering, Chittagong University of Engineering & Technology, Chattogram-4349, Bangladesh
[2]Professor, Department of Mechanical Engineering, Chittagong University of Engineering & Technology, Chattogram-4349, Bangladesh

ABSTRACT

The growing demand for sustainable energy has driven research into alternative materials capable of harvesting mechanical energy. Wood, a biodegradable and renewable resource, exhibits intrinsic piezoelectric properties due to its cellulose microfibrils and dipolar regions. This study investigates the piezoelectric performance of three wood species—Balsa, Pine, and Gamari—enhanced through a chemical delignification process using peracetic acid. The treatment removed 27.05% lignin from Balsa, 39.19% from Pine, and 10.46% from Gamari, while moisture content was reduced by 9.77%, 10.67%, and 10.47%, respectively. These structural changes improved compressibility and enhanced voltage response. Under a 1 kg load, treated Balsa generated up to 300.52 mV, significantly higher than its untreated counterpart (2.3 mV). Treated Pine and Gamari produced 254.56 mV and 149.55 mV, respectively, also showing considerable improvements. The results confirm that delignified wood can serve as an effective and eco-friendly material for energy harvesting. This work addresses a critical gap in current literature by comparing multiple wood species and offers promising insights into their application in self-powered sensors and sustainable building technologies.

Keywords: Piezoelectricity, cellulose, delignification, air gap, lignin.

1. Introduction

Piezoelectricity—the generation of voltage in response to mechanical stress—was first discovered by Pierre and Jacques Curie in 1880. It occurs through asymmetric displacement of ions in materials, inducing electric polarization [1]. Traditionally associated with crystals and engineered ceramics, recent advancements in material science have revealed that certain biological materials, including wood, also exhibit piezoelectric behavior due to the crystalline structure of cellulose microfibrils in their cell walls [2]. While this intrinsic piezoelectricity is limited in untreated wood, it can be significantly enhanced through chemical modification. This study focuses on chemically treated Balsa, Pine, and Gamari wood, selected for their distinct densities and cell wall structures [3] [4]. In their natural state, the tightly bound lignocellulosic matrix in wood restricts deformation, limiting piezoelectric efficiency. To overcome this, a peracetic acid-based delignification process was applied to selectively remove lignin and portions of hemicellulose, resulting in a porous, compressible structure with greater exposure of piezoelectric-active cellulose domains [5]. By evaluating the electromechanical response of the treated samples, this research explores the relationship between structural transformation and voltage generation. Global electricity demand increased by approximately 36% from 2012 to 2022, reaching 28,465 TWh in 2022, according to the International Energy Agency [6] and the limitations of conventional renewable sources like solar power, the development of wood-based piezoelectric materials presents a promising, eco-friendly solution for energy harvesting and self-powered sensing technologies in everyday environments.

1.1 Effect of Air Gap in Wood

1.1.1 Direct Relationship

The presence of air gaps reduces the effective dielectric constant of the wood because air has a much lower dielectric constant (~1.0) compared to the wood matrix. A lower dielectric constant generally means higher electric field strength for a given charge, which can enhance voltage output [7]. Mechanical stress applied to wood is redistributed due to the air gaps. These gaps can concentrate stress in certain regions, which might amplify local piezoelectric responses, increasing voltage generation. More air gaps may lead to a higher localized deformation under stress, enhancing the overall electric charge displacement [8]. If the wood is treated to become piezoelectric, the air gaps can influence how stress is transferred to the piezoelectric regions. Properly distributed air gaps can enhance stress transfer efficiency, leading to higher voltage output.

1.1.2 Non-linear Effects

Excess air gaps can weaken the wood's structural integrity, reducing its ability to effectively transfer mechanical stress. Conversely, too few air gaps may reduce the dielectric benefits, leading to lower voltage generation. An optimal balance exists where the air gap distribution maximizes the voltage output without compromising the mechanical or piezoelectric properties [9]. Interconnectivity of Air Gaps: If the air gaps are interconnected, they might act as channels that reduce the mechanical stress applied to the piezoelectric regions, decreasing voltage output [10].

1.2 Effect of Density on Piezoelectricity

The piezoelectric effect in wood is primarily attributed to the crystalline structure of cellulose microfibrils within the cell walls. Research indicates that both the density of wood and the presence of defects significantly affect its piezoelectric response. Higher density can enhance the piezoelectric effect due to the increased alignment and quantity of cellulose microfibrils, which are responsible for piezoelectricity in wood. Conversely, defects can disrupt this alignment, diminishing the effect [11]. Studies have shown a correlation between the magnitude of the piezoelectric effect and factors such as tree species, wood density, and the position within the tree. This suggests that denser wood species may exhibit stronger piezoelectric responses [12].

The principle and technique behind generating charge or producing voltage from a neutral body in response to different types of mechanical vibration or pressure has been studied considerably. To generate charges more specifically to acquire the piezoelectric effect, the internal structure of the sample such as crystal atoms require being oriented in a particular manner. When pressure is applied to a particular spot, the structure undergoes deformation due to compressibility, changing the orientation of the crystal's positive and negative ions and producing a relative voltage between the oppositely charged zones. Multiple reports have been written about it, and numerous systems have been carried out using it. Advanced research on this effect has been conducted, and more is being done. The piezoelectric effect has been used to generate energy from hardwood flooring, balsa wood microsensors, and other materials. These and other ideas have been discussed in several research articles. Some researchers have even used dry bone as a piezoelectric material. Other materials have been used for advanced research, such as fish skins and spider silk. A group led by Ingo Burgert at Empa – the Swiss Federal Laboratories for Materials Testing and Research – and ETH Zurich has researched that balsa wood can be used as a nanogenerator which produces voltages in response to simultaneous loading unloading [13]. Mahidur R. Sarker *et al.* developed optimized techniques to enhance the performance and generate small voltages of energy from cantilever beam vibrations [14]. Dhananjay Kumar, Pradyumn Chaturvedi and Nupur Jejurika designed and fabricated a piezoelectric energy harvester using commercial piezoelectric and also used a boost converter for boosted output signal [15]. Joje Mar P. Sanchez *et al.* harvested energy through piezoelectric tiles. The comparison of voltage output from different types of piezoelectric tiles is shown [16]. Eiichi Fukada *et al.* analyzed the piezoelectric effect of the bone [17]. Sumanta Kumar Karan et al. researched spider silk as a possible source of highly efficient piezoelectric nanogenerator material [18]. Sujoy Kumar Ghosh *et al.*, have researched the potential of the fish swim bladder and fish scales as a highly efficient piezoelectric generator [19], [20]. For chemical delignification treatment, to produce an oxidizer which is peracetic acid, a 1:4 molar ratio of acetic acid and hydrogen peroxide has been used instead of typical industrial 1:1 molar ratio, according to a research paper known as "Effects of peracetic acid and hydrogen peroxide concentration on kraft lignin degradation at room temperature" published by Se Young Park *et al.*, it would give better performance in delignification rather than other molar ratios [21]. However, the previous work which has been done with balsa only used a 1:1 molar ratio.
Being a fairly it is a new research topic as the energy generation and biosensor application using wood remains an underdeveloped research region. Only the balsa wood is introduced in this field. Here in this study balsa, pine, and gamari wood have been used as raw materials. The selection criteria of wood is based on lower cell wall thickness,airgap,orientation of lignin. As the target is to make the treated wood spongy as much as possible,it is essential to select a wood that has low density and a thin cell wall. The delignification process will take away lignin from the wood sample and hence make it constructed only with cellulose and hemicellulose. That's why pine, balsa and gamari are selected as they have low density and small cell wall thickness. Balsa, pine and gamari have been selected due to their abundant availability. Combining wood with piezoelectric polymers like PVDF (polyvinylidene fluoride) and ensuring optimal air gap structure can result in more efficient voltage generation under mechanical stress [22].

2. Research Methodology

In this study, the wood samples—Balsa, Pine, and Gamari—underwent a chemical delignification process to enhance their piezoelectric properties. Initially, the wood blocks were oven-dried at 105°C for 24 hours to remove moisture. A peracetic acid solution was prepared by mixing acetic acid (98%) and hydrogen peroxide (30%) in a 1:4 molar ratio, with four to six drops of sulfuric acid (99%) added as a catalyst. This solution was stabilized for one hour before use. The wood samples were then submerged in this oxidizing solution for 60 hours to selectively remove lignin and parts of hemicellulose, which resulted in a porous, compressible structure enriched in cellulose. After treatment, the samples were thoroughly washed with distilled water for 48 hours to eliminate residual chemicals and odors. To stabilize the structure, the samples were frozen at below 0°C for 48 hours, followed by a second drying phase at 105°C for another 24 hours. This chemical process exposed more piezoelectric-active cellulose domains, making the treated wood more suitable for energy harvesting applications. The progression of the sample through different processing stages is illustrated in "Fig. 2.1" to "Fig. 2.4".

3. Result and Discussions

The results are organized in a sequential manner, beginning with changes in physical dimensions due to treatment, followed by delignification effects, and culminating in voltage generation behavior across different loads and sample types. Emphasis is placed on identifying patterns in piezoelectric response, understanding the correlation between structural modification and electrical output, and validating the suitability of treated wood for energy harvesting applications. All measurements were taken under consistent laboratory conditions, and data consistency was ensured through repeated trials and calibration of measurement instruments.

3.1 Change in Shape:

After the treatment, a shrinkage in the size of both the samples was noticed. Almost 2 mm shrinkage in radial, tangential and longitudinal directions has been noticed for both Balsa and Gamari wood. As the Pinewood cube is small, it deformed more due to friction with the wall of the glass beaker and gained a new size of almost a hexagonal shape.

Balsa Pine Gamari

Fig. 2.1 Different raw wood samples before chemical treatment

Balsa Pine Gamari

Fig. 2.2 Final state of samples after chemically for 60 hours.

Balsa Pine Gamari

Fig. 2.3 Condition of wood samples after freezing.

Fig. 2.4 Wood coated with conductive ink

3.2 Result of Delignification

After 60 hours of chemical treatment, it's visible that both gamari, pine and balsa wood have changed their characteristics. The blocks of wood become soft, spongy and white. The lignin is completely dissolved in the acidic solution. As the cell wall is made of lignin the structure of wood blocks loses its strength which is why some white debris from the sample can be seen floating over and around the solution. Now it's possible to calculate the reduced weight loss of lignin which has been dissolved as lignin in a chemical acidic solution in the delignification process. “Table 3.1” shows the weight lost as moisture in the over-drying process.

After all chemical treatment, if the samples are oven-dried again, it is be possible to measure the removed lignin content in the samples. Which has been done here exactly. “Table 3.2” shows the weight loss reduction in the delignification process.

Table 3.1 Acceleration vs. frequency of vibration

Wood samples	The average weight of untreated oven dried wood (gm)	The average weight of treated oven-dried wood (gm)	Percentage of lignin weight reduced
Balsa	8.402	7.581	9.77%
Pine	3.409	3.042	10.67%
Gamari	10.89	9.75	10.47%

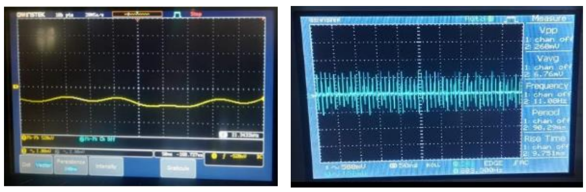
Table 3.2 Percentages of weight reduced in the delignification process.

Wood samples	The average weight of untreated oven dried wood (gm)	The average weight of treated oven-dried wood (gm)	Percentage of lignin weight reduced
Balsa	7.581	5.53	27.05%
Pine	3.042	1.85	39.185%
Gamari	9.75	8.73	10.46%

As balsa, pine and gamari wood contain approximately 10 to a maximum of 31% lignin, it's proven that 100% lignin has been extracted from the sample with a little bit of partial removal of hemicellulose. Pine loses more weight percentage as a result of a little bit of material lost due to friction in the form of debris.

3.3 Voltage Generation:

The peak-to-peak and rms voltage were noted by applying different stress to different wood materials. The voltage varies from machine to machine which indicates an internal error in the machine's reading. The voltage also varies day to day which was a result of temperature change. The data were recorded at a room temperature of 28°C. “Fig. 3.1” demonstrates how the voltage taken applying weights in this study using an oscilloscope.



(a) (b)

Fig.3.1 (a) Oscilloscope display for generated voltage applying 4.9N perpendicular force at untreated balsa’s surface, (b) Oscilloscope display for generated voltage for a single tap with a on the surface of treated balsa wood.

4.4 Voltage Generation from Balsa for Varying Weight

“Table 3.3” shows the generated voltage in response to mechanical force for treated Balsa wood. “Fig. 3.2” shows the graphical representation of voltage generation against weight for balsa wood.

Table 3.3 Voltage generated by balsa

The force is given by the mass (gm)	Voltage, Vrms (mv)
200	91.924
400	137.179
500	212.132
800	263.044
1000	300.52

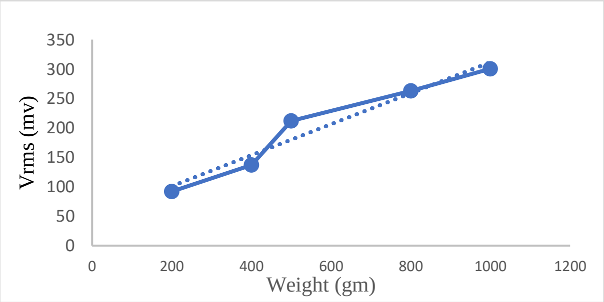


Fig.3.2 Variation of generated voltage in response to weight for treated balsa wood.

From "Fig. 3.2", considering linearity, the formed equation from the graph is: $Y = 0.2635X + 48.149$;
Where, X= Weight(gm) And Y= Voltage(mV)
Where, maximum error happens at the first value where for X=200 gm, Y=100.849 mV and the value of error is 8.85% which is below the maximum accepted error of 10%. So, here Y is proportional to X. With the increment of weight, voltage also increases.

3.5 Voltage Generation from Pine for Varying Weight:

"Table 3.4" shows the generated voltage in response to mechanical force for treated pine wood. "Fig. 3.3" shows the graphical representation of voltage generation against weight for pine wood.

Table 3.4 Voltage generated by pine.

The force is given by the mass (gm)	Voltage, Vrms (mv)
200	113.14
400	134.35
500	145.664
800	212.132
1000	254.56

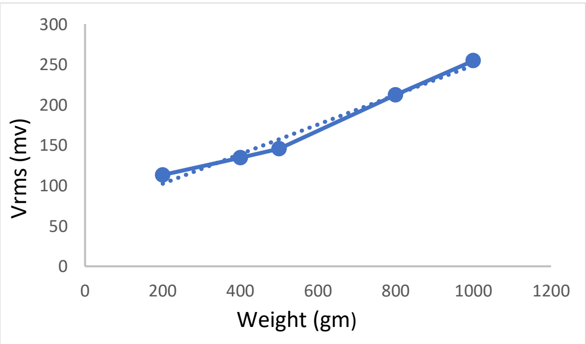


Fig.3.3 Variation of generated voltage in response to weight for treated pine wood.

From "Fig. 3.3", considering linearity, the formed equation from the graph is: $Y = 0.1832X + 65.7$;
Where,X= Weight (gm) And Y= Voltage(mV)
Where, maximum error happens at the first and sixth values and the value of error is 10.55% which is little bit above the maximum accepted error of 10%. But for the ease of analysis, it is considered acceptable.

3.6 Voltage Generation from Gamari for Varying Weight:

"Table 3.5" shows the generated voltage in response to mechanical force for treated gamari wood. "Fig. 3.4" shows the graphical representation of voltage generation against weight for gamari wood.

Table 3.5 Voltage generated by gamari.

The force is given by the mass (gm)	Voltage, Vrms (mv)
200	55.15
400	74.95
500	90.51
800	121.98
1000	149.55

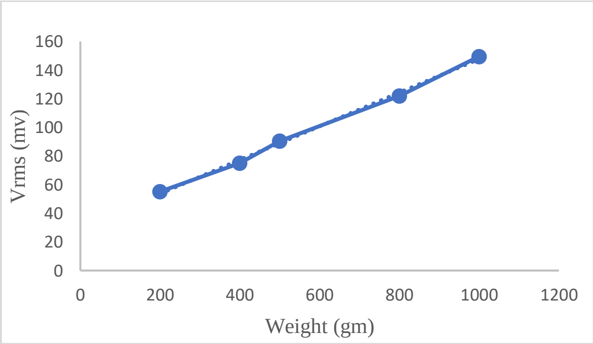


Fig.3.4 Variation of generated voltage in response to weight for treated gamari wood

From "Fig. 3.4" , considering linearity the formed equation from the graph is: $Y = 0.1175X + 30.253$;
Where, X= Weight (gm) And Y= Voltage(mV)
Where maximum error happens at the first and sixth values and the value of error is 2.53% which is less the maximum accepted error of 10% which is acceptable

3.7 Voltage Generation from Untreated Wood:

Untreated balsa in 9.8N perpendicular force at 30×30 area generates 2.3mV whereas treated balsa generates 300.52mV at the same load. Untreated pine in 9.8N perpendicular force at 20×19 area generates a very low peak-to-peak voltage of 520 µV means 367.695 µV rms voltage, whereas treated pine generated 254.56mV at the same load. Untreated gamari in 9.8N perpendicular force at 30×30 area generates around less than 0.295mV whereas treated balsa generates 149.55mV at the same load. Increasing load on the same area or increasing pressure doesn't change the voltage output from untreated raw wood that much.

3.8 Voltage Generation from Varying Wood Samples for the Same Load

The variation in generated voltage as a function of wood type and applied weight is shown in "Fig. 3.5". The treated balsa generated a voltage of 90 to 130 times more than untreated Balsa according to “Fig. 3.5”. The negligible voltage of micro level was noticed from raw untreated pine whereas the significant voltage was harvested from treated pine, almost 250 to 600 times higher than the untreated pine. Also treated gamari wood generates 180 to 500 times more than untreated gamari wood. Comparing both treated balsa, pine and gamari, balsa generates more voltage than pine and gamari applying the same stress.

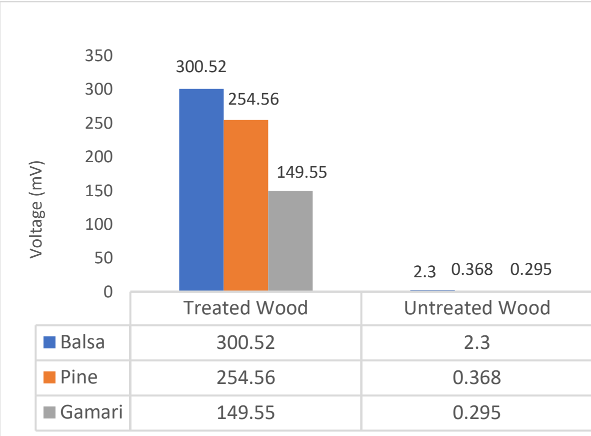


Fig.3.5 Comparison of generated voltage among different treatedd and untreated woods at 1kg weight.

Here, “Fig. 3.6” shows the theoretical comparison of voltage generated among treated balsa, pine and gamari in response to mechanical force via weigth.

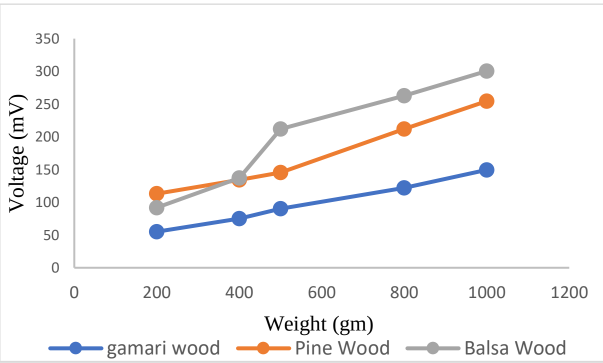


Fig.3.6 Comparison of generated voltage among balsa, pine and gamari for various weight.

Here, the empirical equations have been applied to establish a smoother relationship among those three in terms of voltage generation.

3.9 Piezoelectric Parameters and Electrical Characterization

To further quantify the electromechanical behavior beyond the open-circuit voltages presented earlier, the piezoelectric charge coefficient d_{33} and charge density were derived using standard piezoelectric relations.

The piezoelectric charge constant quantifies the electric charge generated per unit of mechanical stress along the same axis as the poling direction [23]. The direct piezoelectric effect is defined as d_{33} and can be determind by using the Eq. (1) [24].

$$d_{33} = \frac{Q}{F} = \frac{C \cdot V}{F} \qquad (1)$$

where Q is the generated charge (C), F is the applied mechanical force (N), V is the measured open-circuit voltage (V), and C is the sample capacitance (F). The capacitance was estimated using Eq. (2), modeling the delignified wood specimen as a parallel-plate dielectric [25] [26] :

$$C = \varepsilon_0 \mathrm{k} \frac{A}{t} \qquad (2)$$

$here$, $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m, $k = 5.3$ to 5.7 (typical of cellulose film) [25]. An average value of $k = 5.5$ was used. A is the electrode area, and t is the sample thickness. The charge density was determined using Eq. (3).

$$\sigma = \frac{Q}{A} = \frac{C \cdot V}{A} \qquad (3)$$

Using the measured voltages at 1 kg load (9.81 N) from “Fig. 3.5” and the geometric parameters reported in the methodology, the derived electrical parameters for treated samples are summarized in “Table 3.6”.

Table 3.6 Electrical properties of treated samples.

Quantity	Balsa	Pine	Gamari
Area,A (m^2)	9.0×10^{-4}	3.8×10^{-4}	9.00×10^{-4}
Thickness, t	0.03m	0.019m	0.03m
Capacitance,C	1.461×10^{-12} F	0.974×10^{-12} F	1.461×10^{-12} F
Voltage, V (V)	0.30052	0.25456	0.14955
d_{33} (in C/N)	4.48×10^{-14}	2.53×10^{-14}	2.23×10^{-14}
d_{33} (in pC/N)	0.0448	0.0253	0.0223
Charge density, σ $(in$ C/m^2)	4.878×10^{-10}	2.525×10^{-10}	2.42×10^{-10}

3.10 Validation of Experimental Results

To confirm the reliability of the obtained data, the experimental results of this study were validated against the findings reported by Ren et al. in Advanced Functional Materials under the title “Salt-In-Wood Piezoelectric Power Generators” [27]. In that study, both untreated and structurally modified wood samples were tested to evaluate their piezoelectric response under controlled loading conditions.

The authors observed that native (untreated) wood generated an open-circuit voltage of around 5 mV when subjected to a 20 N compressive load, with an effective piezoelectric coefficient of approximately 1.1 pm·V⁻¹. The low output was attributed to limited cellulose chain orientation and constrained ionic polarization within the natural wood cell walls.

After introducing Rochelle salt crystallization through a top-down modification approach, a significant increase in piezoelectric output was reported. The treated wood produced voltages ranging from 1.4 V to 7 V at 20 N, and up to 11 V under 200 N. This enhancement was mainly linked to improved mechanical stress transfer, internal pore development, and the formation of additional piezoelectric crystalline domains in the cell matrix.

In the present investigation, a peracetic acid-based delignification process was employed, which produced a comparable improvement trend but on a smaller voltage scale. The selective removal of lignin and partial dissolution of hemicellulose increased the internal porosity and flexibility of the samples, allowing more efficient mechanical deformation and charge displacement. Under a mechanical load of roughly 9.8 N (equivalent to 1 kg), the recorded voltages were: Treated 254.56 mV (untreated: 0.368 mV), Treated Gamari: 149.55 mV (untreated: 0.295 mV).

Both the current and referenced studies displayed a linear dependence of voltage on applied force, signifying that mechanical deformability and exposure of cellulose-based piezoelectric regions are critical in enhancing electrical output. While Ren et al. achieved volt-level signals through crystal embedding, the present work achieved a similar functional improvement using chemical modification alone, producing millivolt-level outputs characteristic of delignified wood structures.

Overall, the close agreement in the performance trend between the two studies confirms that porosity, internal stress distribution, and activation of cellulose microfibrils are the principal factors governing the piezoelectric enhancement in wood. This alignment substantiates the validity of the current experimental results and situates them within the broader framework of ongoing research on sustainable, wood-derived piezoelectric materials.

5. CONCLUSION

From the above analysis, it's fair to make some statements which are given below: (1) Balsa has been more effective than pine and gamari in terms of higher voltage generation at the same mechanical force. This indicates the fact that the more a wood has compressibility and air gap after chemical treatment the more it will generate voltage. The lower the density of the wood the more it tends to show porous characteristics and hence improve voltage generation. (2) The more the weight increases the more the voltage increases in a linear pattern. (3) The 1:4 molar ratio of acetic acid and hydrogen peroxide delignified 100% with semi removal of hemicellulose which has been proved by "Table 3.2". (4) We can say balsa would be more effective in terms of application where more voltage is needed. (5) Through the derived relations of the piezoelectric charge coefficient (d_{33}), charge density (σ), and capacitance modeling, the study quantified the electromechanical coupling of treated samples. The d_{33} values ranged between 0.0223–0.0448 pC/N, aligning with expected magnitudes for delignified cellulose-based materials.

To further advance the development of wood-based piezoelectric materials, future research should investigate a broader range of wood species, particularly low-density variants with enhanced deformability and voltage responsiveness. Voltages may vary between earlywood and latewood of the same species. In this study, a constant 1 kg load was applied during all measurements to ensure consistency and prevent sample failure, which proved sufficient for measurable outputs while preserving structural integrity. Results show a positive linear relationship between mechanical load and voltage generation due to increased deformation and dipole displacement, suggesting higher outputs under greater loads. Studies with varied loading conditions could optimize force-to-output performance. Voltage generation also depends on force direction, though multi-axis testing was not conducted here. Different molar ratios, temperatures, and durations in chemical treatment can affect results; freeze-drying time influences internal air gaps, making precise control of time and temperature essential. For testing characteristic like wettability, software-based wet-angle analysis is preferable to qualitative methods. Durability is critical—the Pine sample deformed after treatment, so a starting size of at least 30 × 30 × 30 mm is recommended, as Balsa maintained its shape under these dimensions. Voltage can be increased using series connections of multiple samples, which was not explored here. Recovering dissolved lignin from acidic solution could improve economics, while the process remains sustainable since residual acid can be neutralized with a base.

References

[1] J. Curie and P. Curie, "“Development, via pressure, of electric polarization in dielectric crystals,”," *Bulletin de la Société minéralogique de France,* vol. 3, pp. 90-93, 1880.

[2] J. Sun, L. Zhu, Y. Liang, Z. Tian, H. Wang and L. Hu, "Sustainable and Biodegradable Wood Sponge Piezoelectric Nanogenerator for Sensing and Energy Harvesting Applications," *ACS Nano,* vol. 14, no. 11, p. 14665–14674, 2020.

[3] A. Tullus, M. Mandre and H. Tullus, "RELATIONSHIPS BETWEEN CELLULOSE, LIGNIN AND NUTRIENTS IN THE STEMWOOD OF HYBRID ASPEN IN ESTONIAN PLANTATIONS," vol. 44, no. 6, pp. 101-109, 2010.

[4] H. V. Scheller and P. Ulvskov, "Hemicelluloses," *Annual Review of Plant Biology,* vol. 61, no. 1, 2010.

[5] S. Y. Park, S. M. Cho and J. C. Kim, "Effects of peracetic acid and hydrogen peroxide concentration on kraft lignin degradation at room temperature," *BioRes,* vol. 14, pp. 4413-4429, 2019.

[6] I. E. Agency, "Electricity Market Report – March 2023," march 2023. [Online]. Available: https://www.iea.org/reports/electricity-market-report-march-2023.

[7] Q. Dong, X. Song and H. Liu, "Effects of Air Cavity in Dynamic Pressure Sensors: Experimental Validation," *Sensors (Switzerland),* vol. 20, no. 6, p. 1759, 2020.

[8] M. Tiitta, V. Tiitta, M. Gaal, J. Heikkinen, R. Lappalainen and L. Tomppo, "Air-coupled ultrasound detection of natural defects in wood using ferroelectret and piezoelectric sensors," *Wood Science and Technology,* vol. 54, no. 4, pp. 1051-1064, 2020.

[9] M. H. Amiri and K. Asadi, "How Porosity Affects the Performance of Piezoelectric Energy Harvesters and Sensors," *Advanced Physics Research,* vol. 2, no. 2, 2023.

[10] Y. Deng, X. Fan, H. Luo, Y. Wang and K. Wu, "Impact of Air Gap Defects on the Electrical and Mechanical Properties of a 320 kV Direct Current Gas Insulated," *Energies 2023, Vol. 16, Page 4006,* vol. 16, no. 10, p. 4006, 2023.

[11] Plackner and Johannes, "THE CONVERSE PIEZOELECTRIC EFFECT IN WOOD AND CELLULOSE MATERIALS THE PIEZO-EFFECT IN WOOD AND CELLULOSE MATERIALS," Vienna, 2009.

[12] V. A. Bazhenov, "Piezoelectric properties of wood," 1963, pp. 235-235.

[13] J. Sun, H. Guo, G. N. Schädli and K. Tu, "Enhanced mechanical energy conversion with selectively decayed wood," *Science Advances,* vol. 7, no. 11, 2021.

[14] M. R. Sarker, S. Julai, M. F. M. Sabri, S. M. Said, M. M. Islam and M. Tahir, "Review of piezoelectric energy harvesting system and application of optimization techniques to enhance the performance of the harvesting system," *Sensors and Actuators A: Physical,* vol. 300, p. 111634, 2019.

[15] D. Kumar, P. Chaturvedi and N. Jejurikar, "Piezoelectric energy harvester design and power conditioning," *2014 IEEE Students' Conference on Electrical, Electronics and Computer Science, SCEECS 2014,* 2014.

[16] J. C. T. Go, A. K. A. Remolino, J. M. P. Sanchez and K. E. Paz, "Harvesting Energy through Piezoelectric Tiles: A Comparative Study of Wood, Porcelain, and Ceramic Tiles," *EDUCATUM Journal of Science, Mathematics and Technology,* vol. 10, pp. 1-6, 2023.

[17] E. Fukada and I. Yasuda, "On the Piezoelectric Effect of Bone," *Journal of the Physical Society of Japan,* vol. 12, no. 10, pp. 1158-1162, 1957.

[18] S. K. Karan, S. Maiti, O. Kwon, S. Paria, A. Maitra, S. K. Si, Y. Kim and J. K. Kim, "Nature driven spider silk as high energy conversion efficient bio-piezoelectric nanogenerator," *Nano Energy,* vol. 49, pp. 655-666, 2018.

[19] S. K. Ghosh and D. Mandal, "High-performance bio-piezoelectric nanogenerator made with fish scale," *Applied Physics Letters,* vol. 109, no. 10, 2016.

[20] S. K. Ghosh and D. Mandal, "Efficient natural piezoelectric nanogenerator: Electricity generation from fish swim bladder," *Nano Energy,* vol. 28, pp. 356-365, 2016.

[21] S. Y. Park, S. M. Cho, J. C. Kim, C. Hong, G. H. Ryu, G. H. Ryu and I. G. Choi, "Effects of peracetic acid and hydrogen peroxide concentration on kraft lignin degradation at room temperature," *BioResources,* vol. 14, no. 2, pp. 4413-4429, 2019.

[22] C. Yang, S. Song, F. Chen and N. Chen, "Fabrication of PVDF/BaTiO3/CNT Piezoelectric Energy Harvesters with Bionic Balsa Wood Structures through 3D Printing and Supercritical Carbon Dioxide Foaming," *ACS publication,* vol. 13, no. 35, 2021.

[23] Y. T. Team, "Understanding piezoelectric constants d33, k, Qm explained," 2023. [Online]. Available: https://yujiepiezo.com/blog/understanding-piezoelectric-constants-d33-k-qm-explained. [Accessed 10 October 2025].

[24] Q. Guo, G. Z. Cao and I. Y. Shen, "Measurements of Piezoelectric Coefficient d33 of Lead Zirconate Titanate Thin Films Using a Mini Force Hammer," *Journal of Vibration and Acoustics,* vol. 135, no. 1, 1 February 2013.

[25] . K. G. Rosas, A. Azari and C. Soldano, "Carboxymethyl Cellulose as a Sustainable Dielectric Material for Organic Field-Effect Transistors," *ACS Applied Electronic Materials 7 (3),,* vol. 7, no. 3, p. 1277, 2025.

[26] Y. Ren, F. Liu and Y. Zhong, "Top-Down Fabricated Wood-Derived Pressure and Strain Sensors: A Review.," *Advanced Science,* p. 15 of 37, 2025.

[27] J. Garemark, M. Ritter, C. Dreimol, R. L. Laranjeira, R. Kürsteiner, D. V. Glaser, A. Parrilli, . F. Ram, C. Oberschelp, I. Efe, T. Pettersson, M. Trassin, G. Panzarasa and . I. Burgert, "Salt-In-Wood Piezoelectric Power Generators with Circular Materials Design for High-Performance Sustainable Energy Harvesting," *Advanced Functional Materials,* vol. 35, p. 2418454, 2025.