Research Article

The Effects of Microwave Curing on Dielectric Properties of Banana Fiber Reinforced High-Density Polyethylene Composite

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Abstract
This study investigates the dielectric properties of banana fiber reinforced high-density polyethylene composites, both with and without magnesium oxide (MgO) as conductive filler, utilizing microwave curing. Dielectric properties play a crucial role in the design and performance of materials in various fields, including electronics and energy storage systems. The introduction of MgO as a conductive filler significantly enhances the dielectric constant of the composites, resulting in improved electrical energy storage capacity. Microwave curing emerges as a key factor in enhancing dielectric properties. Compared to conventional oven and room temperature curing techniques, microwave cured composites consistently exhibit higher dielectric constants. The dielectric constant of 0.24 at 2 MHz for microwave cured NaOH treated fibers. In addition, the comparison of dielectric permittivity made from oven-cured and microwave-cured composites at relaxation frequencies of 10 kHz exhibited an 11 percent increase through microwave curing. The rapid and volumetric heating properties of microwave curing enable more effective dispersion and distribution of MgO particles within the composites, ultimately enhancing interfacial polarization and dielectric performance.

Keywords: Banana fiber reinforced HDPE, Conductive filler, Dielectric constant, Dielectric loss, Microwave curing

1 Introduction

Dielectric materials, due to their unique electrical insulating properties, play a vital role in the ever-evolving landscape of modern technology. These materials serve as key components in various applications, including electronics, telecommunications, capacitors, and energy storage systems [1]. Achieving controlled dielectric properties has been a significant focus on materials science and engineering. This pursuit has led to the exploration of sustainable and cost-effective solutions. Natural fiber reinforced polymer composites stand out as a promising candidate, owing to natural fiber as eco-friendly, lightweight nature, affordable, biodegradable, and excellent mechanical properties [2]. However, achieving controlled dielectric properties in such composites remains a formidable challenge. Besides that, natural fiber is also known for its hydrophilic nature, which leads to poor compatibility between the fibers and polymer matrices. These drawbacks can be eliminated by surface chemical treatment [3].

Surface chemical treatment of the fibers is a critical aspect of this investigation. It involves the modification of fiber surfaces to improve their compatibility with the polymer matrix. Such treatment is known to remove impurities, thereby boosting the hydrophobicity properties of the fiber and enhancing the bonding between the polymer matrix and natural fiber [4]. These modifications can ultimately lead to improved dielectric performance. Some methodologies that were employed in recent years have been a testament to improved chemical composition within numerous natural fibers through mercerization (alkali

treatment). Tengsuthiwat *et al*. and Vijay *et al*., conducted analysis of alkali treatment and numerical studies on natural fiber reinforced polymer composites where post-chemical treatment was scrutinized, and crucial deductions were acquired from their evaluations. In turn, their studies reveal that after chemical modification, composition of cellulosic structures drastically increased compared to untreated fibers. On the other hand, the numerical/experimental study helped to understand that biofiller based fabrics/epoxy composites exhibit an expected tensile property with minor void formation. Analytical data from ANSYS revealed that stress distribution epoxy-fabric layer to the filler surface indicated less towards failure and more towards fibers being highly taut when observed under a microscope [5], [6].

The introduction of magnesium oxide (MgO) as a conductive filler holds immense potential in this study. MgO is renowned for its excellent dielectric properties, making it an attractive choice to enhance the electrical behavior of these composites. Moreover, the utilization of conductive filler offers a cost-effective solution, particularly advantageous in applications demanding electrical conductivity [7]. The effectiveness of the bond between the polymer and metal filler heavily relies on the physical and chemical attributes of the filler, as well as the surface-to-volume ratio of the metal particles. Smaller metal particles offer a larger surface area, which promotes greater physical and chemical interactions, thus enhancing the interfacial adhesion of the composites. Additionally, conductive fillers help reduce the presence of voids in the composites, further improving their overall quality and performance [8]. A study was done on the effect of dielectric properties of adding conductive fillers in natural fiber reinforced polymer composites. They found that adding the fillers increased the suitability of the composites for electromagnetic absorption. Additionally, the introduction of the fillers improved both the complex permittivity and loss tangent of the composite [9].

Furthermore, microwave curing is investigated as a processing method to optimize the dielectric performance of these composites. Microwave curing, with its rapid and volumetric heating properties, is explored for its potential to achieve effective dispersion and distribution of MgO particles within the composites [9]. This, in turn, can lead to better interfacial polarization and improved dielectric performance.

Through systematic experimentation and analysis, this research aims to unravel the effect of these processes and their combined influence on the dielectric properties of the composites. Besides, the hypothesis for this study was implemented and a logical methodology was employed. Figure 1 shows the methodology for the fabrication of HDPE-MgO-Banana natural fibers composites and their corresponding evaluations. The insights gained from this study have the potential to revolutionize the development of sustainable and high-performance dielectric materials, ushering in a new era of advanced technological applications and eco-friendly solutions.

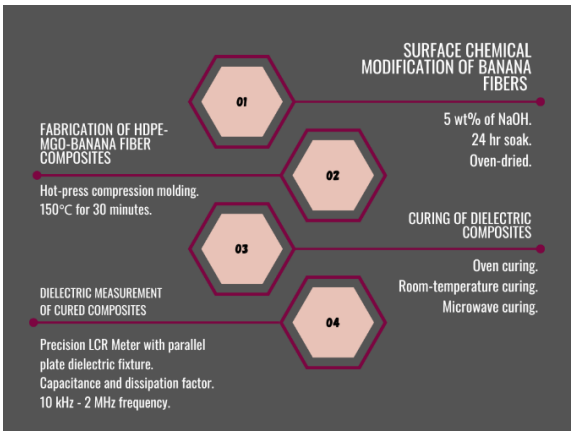

Figure 1: Process flow of the methodology employed.

2 Materials and Methodology

2.1 *Materials*

The materials used in this study are banana fibers, high-density polyethylene (HDPE) pellets and magnesium oxide (MgO) powder. The banana fibers were locally purchased in Sarawak, Malaysia and the HDPE and MgO were obtained from Opalene HDPE and Sigma-Aldrich Sdn. Bhd., respectively. furthermore, the fibers were subjected to three different chemical treatments: potassium hydroxide (KOH), calcium carbonate ($CaCO_3$), and sodium hydroxide (NaOH), sourced from Germany, India, and USA, respectively.

2.2 *Treatment of Fibers*

The banana fibers were shortened to lengths no longer than 5 mm and washed with distilled water to eliminate any surface impurities. They were dried in an oven at 60 ℃ for 48 h. Following drying, the fibers were evenly divided for surface chemical treatment. For the NaOH treatment, a 5 wt% NaOH reagent was

created by dissolving 50 g of caustic soda pellets in 1 L of distilled water. The natural fibers were then soaked in this solution for 24 h at room temperature. Then, the fibers were washed with distilled water and were subjected to a 48-h drying period at 60 ℃ [10]–[12].

2.3 *Fabrication of composites*

The composites were fabricated by using a hot press compression machine for both untreated and treated fiber reinforced HDPE composites with and without MgO as conductive filler. The fibers were loaded into the mold at a concentration of 25wt% with random orientation as it has the lowest dielectric constant and dielectric loss. The mold adheres to ASTM standard D150, featuring a diameter of 50 mm and a thickness of 5mm. This composite was then subjected to varying loadings of MgO at concentrations of 2, 4, 6, 8, and 10 wt%. the hot press was set to 150 ℃, applying 15 Tons of pressure for 30 min. Then, the mold was cooled for an hour in the open air. Following that, the samples were placed in a re-sealable airtight storage bag in preparation for curing.

2.4 *Curing of composites*

This study utilized three curing techniques: microwave curing, oven curing, and room temperature curing. A Samsung MS23K3513AK microwave was used, with samples cured at 600 W for 3 min as it shows more significant results. Oven curing was performed at 70 ℃ for 60 min, while room temperature curing lasted for 2 h.

2.5 *Dielectric properties testing*

The dielectric characteristics of the composite materials were evaluated using the Agilent E4980A Precision Induction, Capacitance, and Resistance (LCR) analyzer along with the Agilent 16451 B Dielectric Test Fixture, as illustrated in Figure 2(a) and (b). These instruments were employed to measure capacitance and dissipation factor, which were then utilized to determine the dielectric constant and dielectric loss of the composites. During the analysis, the samples were positioned between two electrodes, and measurements were taken at various frequencies, including, 10 kHz, 50 kHz, 100 kHz, 150 kHz, 1MHz, 1.5 MHz, and 2 MHz. Ensuring no gaps exist in this methodology is crucial. To improve measurement precision, the testing protocol involved repeating the procedure with the sample inverted to acquire a second set of readings, and subsequently calculating the average of these values.

(a) (b)

Figure 2: (a) Agilent E980A Precision LCR, and (b) Agilent 16451 B Dielectric Test Fixture.

3 Results and Discussion

3.1 *Dielectric constant of composites*

Figures 3, 4, and 5 show the dielectric constant of composites subjected to room temperature curing, oven curing, and microwave curing, respectively. This result shows that the pure HDPE consistently exhibits the lowest dielectric constant across all frequencies. However, as banana fiber is introduced into the composites, there's a noticeable rise in the dielectric constant at lower frequencies and a decline at higher frequencies. For instance, at 1 kHz at room temperature, the NaOH composites sample showed a 25% increase in dielectric constant compared to the pure HDPE sample. Furthermore, the composites with treated fibers display a lower dielectric constant, approximately 8% lower than that of the untreated fiber composite. This decrease is attributed to the increased hydrophobicity of the fibers resulting from surface chemical treatment that has been illustrated in some of the literature that has been reviewed. This is in line with the observations made in the graphs and aligns with a discussion by Ahmad *et al*. [9].

Chemical treatment disrupts the hydrogen bonds within the fibers, enhancing fiber hydrophobicity and reducing orientation polarization, ultimately resulting in a lower dielectric constant. Moreover, across all three graphs, it is noticeable that as the frequency rises, the dielectric constant of the composites decreases. This phenomenon is linked to the dipole relaxation within the composites as the frequency rises [13].

In Figure 3, NaOH composites exhibit a higher dielectric constant than HDPE composites, KOH composites, and $CaCO_3$ composites. This difference can be attributed to the fact that the surface chemical treatment may not entirely eliminate hydrogen bonds [14]. Consequently, due to their hydrophilic nature, these fibers have the capacity to absorb moisture from their surroundings, leading to an increase in the conductivity of the composites. Moreover, although the presence of $CaCO_3$ might affect the mechanical properties of the composites, it does not appear to directly influence the dielectric constant.

Figures 3 and 4 reveal a significant difference between room temperature cured composites and oven cured composites. Room temperature curing results in composites with a higher dielectric constant, approximately 13% compared to oven cured composites. This distinction arises because oven curing involves elevated temperatures, which facilitate more extensive cross-linking of the polymer matrix and densification, thereby reducing free space, and consequently, lowering the dielectric constant [15]. Additionally, Figure 3 shows that untreated fiber composites exhibit higher dielectric constant than treated fiber reinforced HDPE composites. This difference can be attributed to the presence of impurities, wax, and lignin on the surface of the untreated fibers, which enhance their polarizability.

Moreover, Figure 4 demonstrates a notable rise in the dielectric constant with increasing frequency for KOH and NaOH composites compared to room temperature and oven temperature. For instance, at 10 kHz, microwave cured KOH and NaOH composites showed approximately 1% and 4–15% increments compared to room temperature and oven cured composites, respectively. This phenomenon can be attributed to the volumetric heating effect achieved by microwave curing, which uniformly heats the entire composite thickness, thereby enhancing the bonding between fiber and polymer matrices at the interface. Furthermore, microwave curing might induce molecular alignment and polarization within the composite, resulting in an overall elevation in the dielectric constant [9].

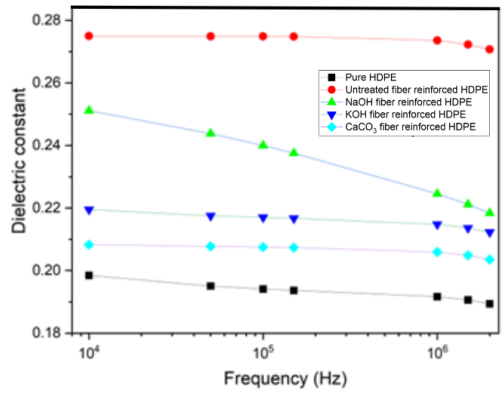

Figure 3: Dielectric constant of room temperature cured composites.

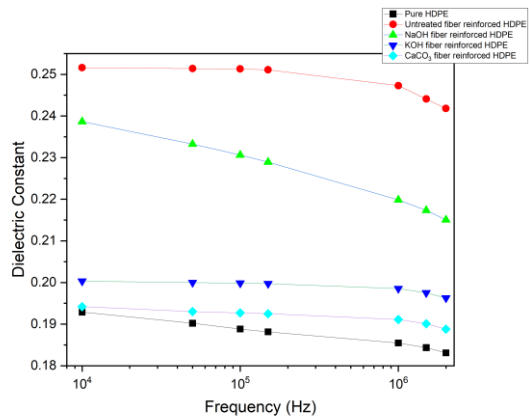

Figure 4: Dielectric constant of oven cured composites.

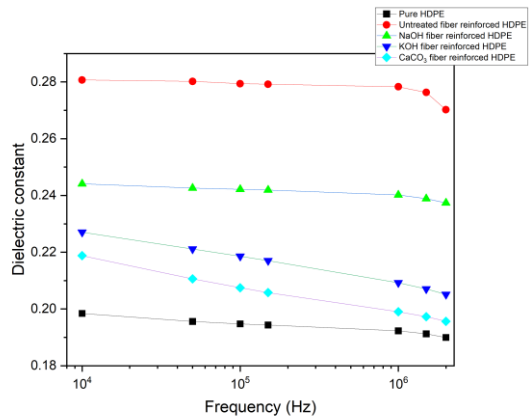

Figure 5: Dielectric constant of microwave cured composites.

3.2 *Dielectric loss of composites*

Figures 6–8 show the dielectric loss of composites subjected to room temperature curing, oven curing, and microwave curing, respectively. When comparing the three graphs, a consistent pattern emerges, indicating that pure HDPE demonstrates the lowest dielectric loss compared to other composites. This can be attributed to the unique molecular structure and the nature of the chemical bonds in HDPE. HDPE primarily consists of carbon and hydrogen atoms linked by nonpolar covalent bonds, resulting in the absence of a permanent electric dipole moment. The even sharing of electrons between bonded atoms contributes to these characteristics. Additionally, HDPE possesses a highly crystalline structure with densely packed polymer chains, minimizing the presence of voids and free spaces within the material, ultimately leading to lower dielectric loss.

The figures suggest that untreated composites demonstrate the highest dielectric loss compared to other room temperature cured composites. This can be attributed to the presence of unwanted components on the surface of the fiber, which can dissipate energy as heat and create localized areas of elevated electrical resistance when exposed to alternating electric fields. Additionally, $CaCO_3$ composites exhibit lower dielectric loss compared to other composites, owing to the relatively low dielectric constant of $CaCO_3$ itself [16]. When utilized as a chemical treatment or filler in composites, $CaCO_3$ can reduce the overall permittivity of the composite, resulting in decreased dielectric losses [14].

NaOH composites demonstrate higher dielectric loss than KOH composites across all curing techniques. For instance, at 10 kHZ at microwave curing, the NaOH composite showed a higher dielectric loss, approximately 12% more than the KOH composite. Although both chemical solutions are strong alkalis, they differ in their ionic strengths. NaOH contains sodium ions (Na^+), while KOH contains potassium ions (K^+). The ionic strength of a solution is directly linked to the concentration of ions, and NaOH solutions generally exhibit higher ionic strength than KOH solutions at the same molar concentration. Consequently, a higher ionic strength can lead to increased ionic conduction and higher dielectric loss [17].

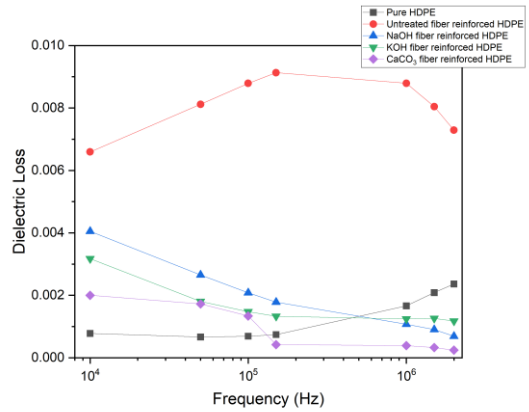

Figure 6: Dielectric loss of room temperature cured composites.

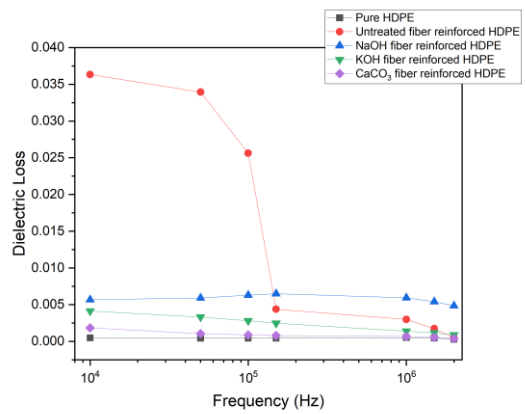

Figure 7: Dielectric loss of oven cured composites.

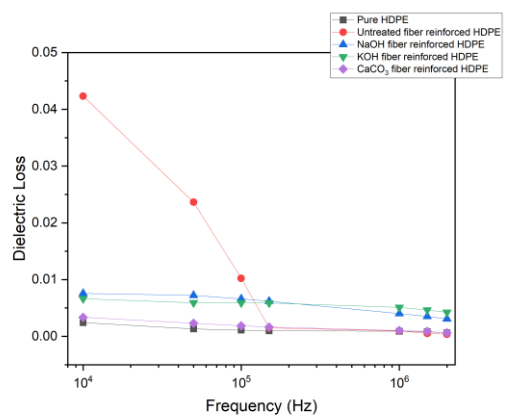

Figure 8: Dielectric loss of microwave cured composites.

3.3 *Dielectric constant of conductive filler composites*

Figures 9–12 show the dielectric constant of $CaCO_3$ composites, featuring varying concentrations of MgO filler. In Figure 8, an observable trend is that, as the MgO filler concentration increases, the dielectric constant also increases. This phenomenon is attributed to the heightened conductivity and increased relaxations within the composite as the MgO filler concentration rises. Furthermore, an increase in MgO concentration enhances the polarization effect within the composite when subjected to an electric field. The MgO particles become polarized, and a higher concentration intensifies this polarization, ultimately resulting in a higher dielectric constant. Figure 11 also showed that microwave cured composites with 8% MgO filler exhibited the highest dielectric constant. This outcome may be attributed to the incomplete heating of composites with 10% MgO filler, which failed to fully combine with the fibers and polymer. For instance, at 10 kHz at microwave curing, the dielectric constant of 8% MgO filler showed approximately 2% more than the 10% MgO filler. In Figure 10, a similar increase in dielectric constant was noted at 2% MgO filler concentration from 10 kHz to 50 kHz. This phenomenon can be attributed to interfacial polarization within the composite, mirroring the observations in Figure 10 at 10% MgO filler concentration from 1 MHz to 1.5 MHz.

Furthermore, it is observed in Figure 8 that the dielectric constants of composites containing 2% to 8% MgO filler concentrations are lower than those of $CaCO_3$ composites without MgO filler. This could be attributed to the presence of MgO at the fiber-polymer interface, which enhances interfacial adhesion and reduces interfacial polarization, ultimately resulting in a decrease in the dielectric constant [7]. Similar reductions in dielectric constant can be observed in the case of the 2% MgO filler concentration in oven cured composites and the 2% to 4% MgO filler concentrations in microwave cured composites.

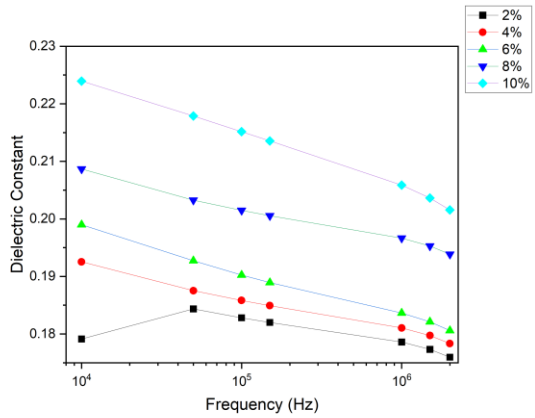

Figure 9: Dielectric constant of room temperature cured conductive fillers composites.

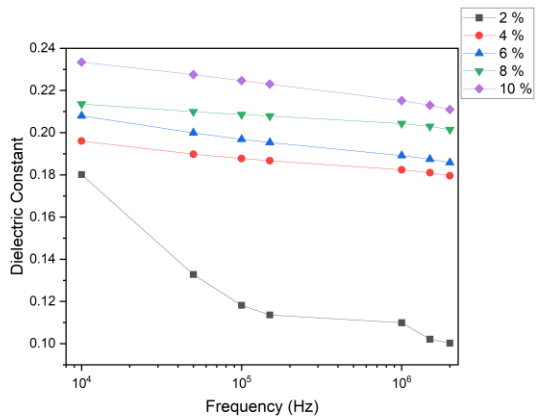

Figure 10: Dielectric constant of oven cured conductive fillers composites.

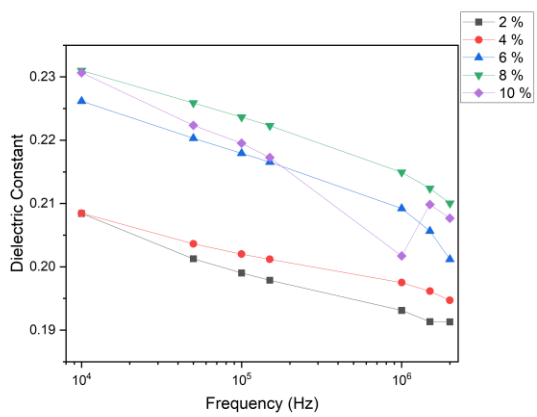

Figure 11: Dielectric constant of microwave cured conductive fillers composites.

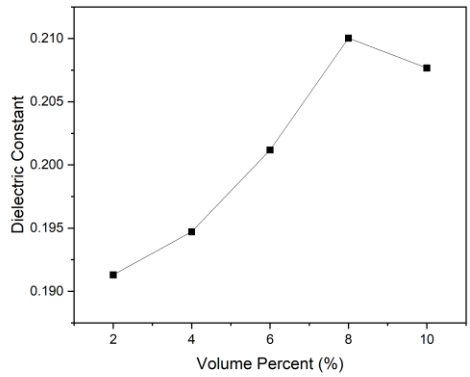

Figure 12: Dielectric constant of microwave cured MgO volume percent composites.

In Figures 9–11, microwave cured composites consistently demonstrate higher dielectric constants compared to oven cured and room temperature cured composites, with differences ranging approximately from 7% to 11% at 10 kHz. Microwave curing is well known for its rapid and volumetric heating capabilities. Consequently, when MgO is incorporated into the composites and exposed to microwave energy, it leads to more effective dispersion and distribution of MgO particles within the composites [9]. This results in increased interfacial polarization and dielectric constant. Moreover, the microwave curing process promotes polarization of the MgO particles and the composite, further increasing the dielectric constant by enhancing the composite's ability to store electrical energy when subjected to an applied electric field.

4 Conclusions

In conclusion, this investigation into the dielectric properties of banana fiber reinforced HDPE composites, both with and without MgO as a conductive filler, using microwave curing, has yielded valuable insights. Notably, the study focused on the dielectric constant and dielectric loss of these composites, leading to several significant observations. The inclusion of MgO as a conductive filler resulted in a significant rise in the dielectric constant. With increasing MgO concentration, the composite's capability to store electrical energy under an applied electric field improved, leading to heightened dielectric constants. Moreover, microwave cured composites consistently demonstrated higher dielectric constants compared to oven cured and room temperature cured composites. The rapidness and volumetric heating characteristics of microwave curing facilitated more effective dispersion and distribution of MgO particles within the fiber and polymer matrices. This improvement heightened interfacial polarization and the dielectric constant, emphasizing the role of microwave curing in enhancing dielectric properties. Overall, this study shows the potential of microwave cured banana fiber reinforced HDPE composites with MgO in applications requiring controlled dielectric properties. In conclusion, three different curing techniques could be employed in the fabrication of new polymer-based composites with natural fibers as reinforcements. Each method had a profound effect on the dielectric properties of the fabricated composites, and it creates value for the hypothesis that has been introduced to understand how curing techniques may or may not improve the dielectric properties of polymer composites. This research contributes to the development of eco-friendly and cost-effective dielectric materials for various technological domains, including electronics and energy storage.

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Author Contributions

T.L.S.M.: conceptualization, investigation, research design, methodology, writing an original draft, data analysis; E.J: writing - reviewing and editing; S.K.H.: writing - editing; J.S.: reviewing and editing; H.P. - writing - reviewing and editing.

Conflicts of Interest

No conflict of interest has been declared.

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