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RESEARCH ARTICLE

Interaction effects of silica incorporation and processing parameters on dielectric loss in pineapple leaf-epoxy composites at 5 GHz

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Abstract - Bio-based dielectric composites have attracted increasing interest as sustainable substitutes for conventional microwave materials, but controlling dielectric loss through the interplay of processing and formulation parameters is still a significant challenge. This work studies the interaction effects of silica addition and processing parameters on the dielectric properties of pineapple leaf-epoxy composites at 5 GHz. The effects of volume of sodium hydroxide solution, soaking time, silica loading, and pineapple leaf fiber powder loading were evaluated using a two-level factorial analysis. Dielectric characterization was performed using a vector network analyzer and a rectangular waveguide. The loss tangent values of the resulting composites were 0.00959 to 0.05894, and the permittivity values were 2.83 to 3.39. The analysis of variance confirmed the statistical significance of the developed factorial model ($p = 0.0064$) with an adjusted R^2 of 0.9999. Additionally, the formulated compositions investigated, the smallest loss tangent of 9.59122×10^{-3} was obtained using 450 mL sodium hydroxide solution, 30 min soaking time, 4 g silica loading, and 30 g pineapple leaf fiber powder loading. The results suggest that the dielectric performance of pineapple leaf-epoxy composites is controlled by the interplay of processing conditions and material formulation, providing therefore a systematic framework for the development of sustainable dielectric materials for microwave substrate applications.

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1. Introduction

Dielectric materials are important for high-frequency systems such as microwave antennas, where the dielectric properties have a strong influence on signal integrity and power transmission efficiency [1], [2]. Among these properties, the loss tangent (tan δ), also called the dissipation factor, is one of the most important parameters, as it indicates the fraction of electromagnetic energy dissipated as heat rather than stored in the material. For microwave systems at about 5 GHz, a low tangent loss is needed to reduce signal attenuation and ensure stable electromagnetic performance [3]. The loss tangent is the ratio of the imaginary part to the real part of the complex permittivity, as in Eq. (1).

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \tag{1}$$

where ε' represents the real part of the permittivity associated with energy storage, while ε'' represents the imaginary part associated with dielectric loss. The growing environmental concerns have accelerated the development of sustainable dielectric materials from renewable sources and agricultural waste. Natural fiber-based composites have emerged as promising alternatives to conventional dielectric substrates due to their renewability, low cost, biodegradability and environmental impact reduction [3]. Different natural fibers have been studied, and pineapple leaf has gained a lot of attention because it is a very abundant agricultural by-product and has good mechanical properties [4]. In our previous study, two-level factorial analysis (TLFA) was used to identify the significant processing variables influencing the dielectric properties of pineapple leaf–epoxy composites [5]. The composites showed a permittivity appropriate for microwave substrate applications. Nevertheless, the measured loss tangent was still relatively high, ranging from 0.028 to 0.085 at 5 GHz, and should be improved in order to obtain low-loss dielectric materials.

The use of inorganic fillers, such as silica, is a promising approach to reducing dielectric loss. Silica has been widely studied as a dielectric modifier for dielectric composites owing to its inherent low dielectric loss, high chemical stability and good compatibility with polymer matrix [6]. Previous work has shown that silica incorporation can improve interfacial bonding, inhibit dipolar mobility, and reduce energy dissipation associated with polarization while maintaining a

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relatively stable permittivity. However, the efficiency of silica is not only dependent on its loading, but also on the processing conditions influencing the fiber–matrix interactions and the obtained dielectric response. The dielectric behaviour of heterogeneous composites is governed by a number of polarization mechanisms like electronic, ionic, dipolar and interfacial polarization. One of the mechanisms is the interfacial polarization of Maxwell-Wagner-Sillars (MWS), which plays an important role in the case of fiber-reinforced composites, since charge builds up at the interfaces of the constituents with different electrical properties [7]. Therefore, the dielectric response is not only dependent on the intrinsic properties of the constituents but also a result of the competition between silica incorporation and processing conditions. Although silica has been widely used as a filler in natural fiber composites to enhance the dielectric performance, systematic studies on the influence of silica loading and processing parameters on dielectric loss in pineapple leaf–epoxy composites are scarce. Since dielectric loss is affected by coupled polarization mechanisms, evaluation of silica loading alone may not be adequate to explain the dielectric behaviour of the composite system. The factorial experimental design enables the evaluation of both main and interaction effects simultaneously, providing a more complete understanding of the governing variables of the dielectric behaviour than evaluating the individual variables independently [8], [9]. The study therefore aims to investigate the interaction effects of silica loading and processing parameters, sodium hydroxide solution volume and soaking time, on the dielectric properties of pineapple leaf–epoxy composites at 5 GHz using the TLFA. Loading of pineapple leaf fiber powder was introduced as an additional formulation parameter to study the combined effect of material formulation and processing conditions on dielectric loss. The results are expected to provide deeper insight into the interaction between silica incorporation and processing parameters in reducing dielectric loss, thereby supporting the development of sustainable low-loss dielectric composites for microwave applications.

2. Materials and Methods

The effect of processing and formulation variables on the dielectric properties of pineapple leaf–epoxy composites was systematically studied by the two-level factorial analysis (TLFA). The experimental approach included formulation design, composite fabrication, dielectric characterization and statistical analysis. Dielectric measurements were conducted using a vector network analyzer coupled with a rectangular waveguide operating at 5 GHz and the experimental responses were analyzed by Design-Expert software to determine statistically significant main and interaction effects controlling the dielectric loss.

2.1. Factorial Design and Composite Fabrication Workflow

The entire experimental workflow is illustrated in Figure 1. The study commenced with the development of a two-level factorial design to determine the combinations of sodium hydroxide solution volume, soaking time, silica loading and pineapple leaf fiber powder loading investigated in this work. The pineapple leaf–epoxy composite samples were fabricated based on the experimental design through sequential fiber treatment, material mixing, mould casting, and curing before dielectric characterization. This workflow ensured that all composite samples were prepared under the same processing conditions prior to the dielectric measurements and statistical evaluation.

2.2. Collection of Pineapple Leaf

Pineapple leaves were collected from a pineapple plantation in Pekan, Pahang, Malaysia. The harvested leaves were thoroughly washed with distilled water to remove surface contaminants and debris prior to alkaline treatment.

2.3. Alkaline Treatment on Pineapple Leaf

The pineapple leaves, after harvesting [9], were cut into sections of about 30 mm in length before alkaline treatment. 5 wt.% sodium hydroxide (NaOH) solution was prepared by dissolving sodium hydroxide in distilled water as shown in Eq. (2).

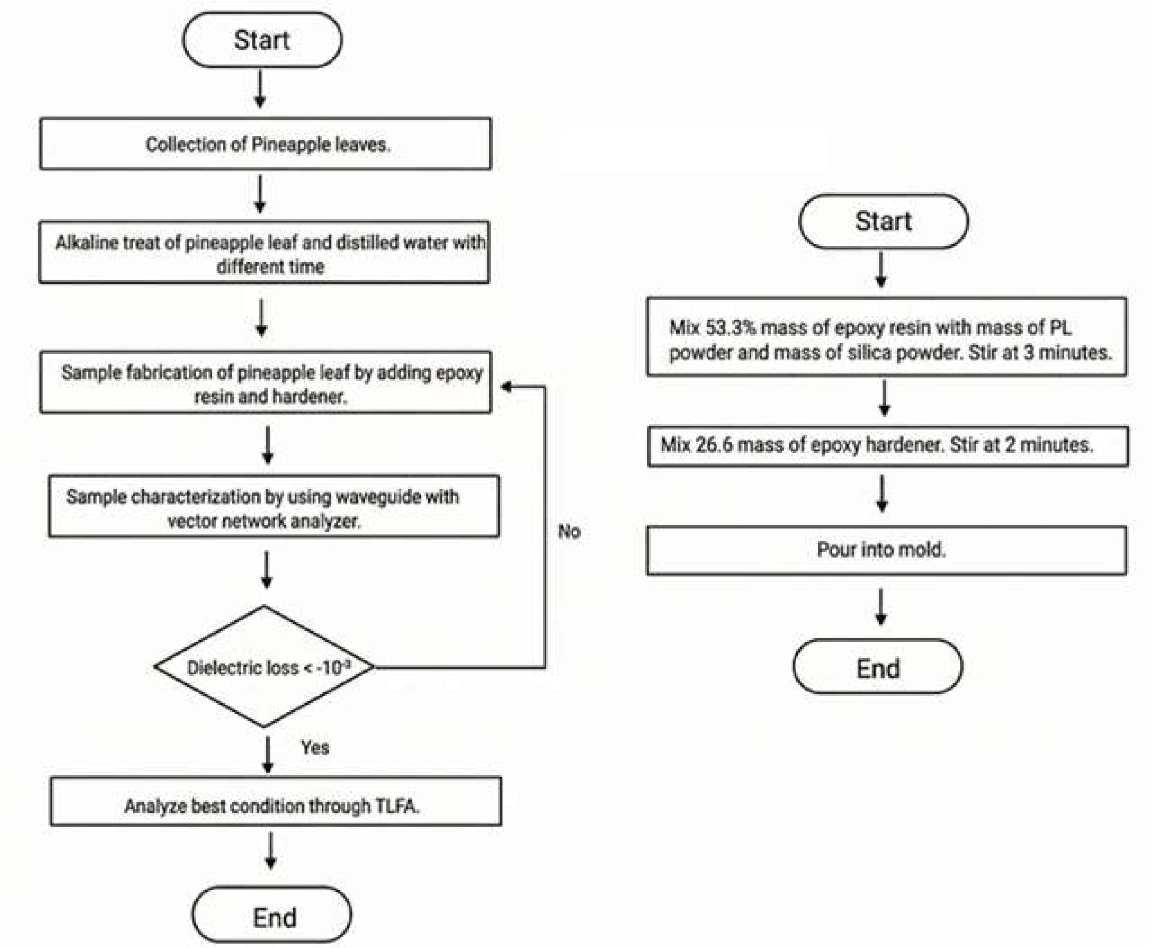
$$5\,wt.\% = \frac{Mass\ of\ NaOH}{Mass\ of\ distilled\ water} \times 100\% \tag{2}$$

In the TLFA, the volumes of sodium hydroxide solution (300 and 450 mL) and soaking time (30 and 120 min) were chosen as processing variables. The pineapple leaf sections were soaked in the prepared NaOH solution under the given conditions to remove non-cellulosic components and to improve fiber separation. After alkaline treatment, the fibers were washed thoroughly with distilled water to remove any residual alkali, filtered, and then oven-dried at 60°C for 24 h to minimize the amount of residual moisture before grinding and sieving for composite fabrication.

2.4. Fabrication of Composite

Composite samples were prepared based on the TLFA of four independent variables, namely, NaOH solution volume, soaking time, silica loading, and pineapple leaf fiber powder loading. As presented in Table 1, each variable was assessed at two levels. The experimental design yielded 16 formulation combinations (Table 2) to assess the main and interaction effects of the selected variables on the dielectric properties of the composites. The experimental runs were randomized in the order of execution using Design-Expert software to minimize any possible bias during the sample preparation and dielectric characterization. After the alkaline treatment as described in Section 2.3, the pineapple leaves were oven-dried, ground, and sieved to get the pineapple leaf fiber powder. Depending on the experimental formulation, 15 g or 30 g of the fiber powder was incorporated into the composite along with silica loadings of 4 g or 8 g.

The epoxy matrix was approximately 80 wt.% of the total composite and consisted of 53.3 wt.% of epoxy resin (SM828) and 26.6 wt.% of polyamide resin 651 hardener. The silica and pineapple leaf fiber powder were added gradually to epoxy matrix under continuous mechanical stirring for about 3 min to facilitate homogeneous dispersion with minimum air entrapment. The resultant mixture was poured into a 22.15 mm by 22.15 mm mould and cured under ambient conditions before dielectric characterisation. Figure 2 illustrates the general procedure of fabricating the composite.



(a) (b)

Figure 1. Experimental workflow showing (a) the TLFA adopted for formulation planning and (b) the composite fabrication procedure prior to dielectric characterization

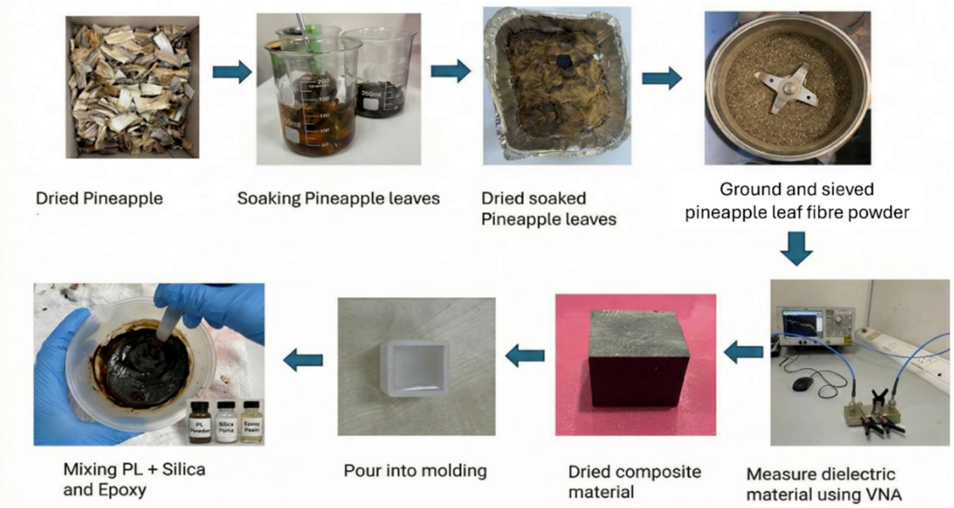


Figure 2. Composite fabrication procedure

Table 1. Experimental variables used in the two-level factorial analysis

Variable	Variable Description	Levels
A	NaOH solution volume	300 mL and 450 mL
B	Soaking time	30 min and 120 min
C	Silica loading	4 g and 8 g
D	Pineapple leaf fiber powder loading	15 g and 30 g

Table 2. Experimental matrix of the two-level factorial analysis

STD	Variable A (mL)	Variable B (min)	Variable C (g)	Variable D (g)
1	300.00	30.00	4.00	15.00
2	450.00	30.00	4.00	15.00
3	300.00	120.00	4.00	15.00
4	450.00	120.00	4.00	15.00
5	300.00	30.00	8.00	15.00
6	450.00	30.00	8.00	15.00
7	300.00	120.00	8.00	15.00
8	450.00	120.00	8.00	15.00
9	300.00	30.00	4.00	30.00
10	450.00	30.00	4.00	30.00
11	300.00	120.00	4.00	30.00
12	450.00	120.00	4.00	30.00
13	300.00	30.00	8.00	30.00
14	450.00	30.00	8.00	30.00
15	300.00	120.00	8.00	30.00
16	450.00	120.00	8.00	30.00

2.5. Material Characterization

Dielectric characterization can be performed using free-space, resonant, or waveguide-based measurement techniques [10]. The waveguide transmission method used in this study is shown in Figure 3. The vector network analyzer (VNA) was connected to a rectangular waveguide. This measurement setup enables dielectric characterization in the frequency range of 4-6 GHz. The composite samples were prepared with a size of 22.15 mm × 22.15 mm to fill the entire cross-sectional area of the rectangular waveguide. Each of the samples was prepared with smooth and parallel surfaces to ensure proper contact with the waveguide and minimize the uncertainty in the measurement. In the rectangular waveguide, only the dominant transverse electric (TE_{10}) mode propagated within the operating frequency range.

Before measurement, the VNA was calibrated using a full two-port short-open-load-thru (SOLT) calibration procedure [11], [12]. The transmission coefficient (S_{21}) was measured in the 4-6 GHz frequency range, and the complex permittivity was obtained from the measured S_{21} response using a waveguide iterative inverse calculation method. Then the extracted complex permittivity was used to calculate the corresponding loss tangent.

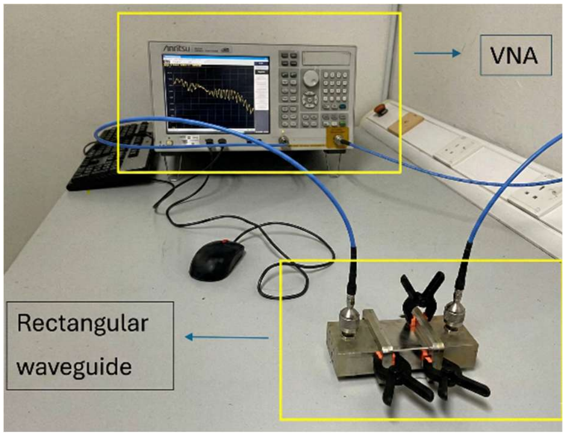


Figure 3. Measurement setup using a VNA and a rectangular waveguide

2.6. Statistical Analysis

The experimental results were analyzed by using Design-Expert software on the basis of TLFA. This statistical approach was used to evaluate the main and interaction effects of the selected processing and formulation variables on dielectric properties of the pineapple leaf–epoxy composites. Statistical significance of the developed model and individual model terms was evaluated by analysis of variance (ANOVA). The adequacy of the model was evaluated by the coefficient of determination (R^2), adjusted R^2, predicted R^2, and their respective *p*-values. Statistical significance was considered at $p < 0.05$ in the model. Then, the fitted statistical model was utilized to calculate the impact of NaOH solution volume, soaking time, silica loading, and pineapple leaf fiber powder loading on permittivity and loss tangent. Main effect plots, interaction plots, Pareto charts, and response surface analyses were used to interpret the effect of individual variables and their interactions on the dielectric performance of the fabricated composites.

3. Results and Discussion

3.1. Two-Level Factorial Analysis of Dielectric Loss

The measured values of permittivity and loss tangent (tan δ) for 16 experimental runs are summarized in Table 3. The fabricated composites showed the permittivity values in the range of 2.83–3.39 and loss tangent values in the range of 0.00959–0.05894 at 5 GHz. The results showed that the dielectric behaviour of the pineapple leaf-epoxy composites was affected by processing conditions as well as the material formulation.

Table 3. TLFA runs with the loss tangent and permittivity results

STD	A: NaOH solution volume (mL)	B: Soaking time (min)	C: Silica loading (g)	D: Pineapple leaf fiber powder loading (g)	Loss tangent	Permittivity
1	300.00	30.00	4.00	15.00	0.01543	3.00665
2	450.00	30.00	4.00	15.00	0.01599	2.83055
3	300.00	120.00	4.00	15.00	0.03169	3.1141
4	450.00	120.00	4.00	15.00	0.01637	3.06006
5	300.00	30.00	8.00	15.00	0.01161	3.04158
6	450.00	30.00	8.00	15.00	0.01035	2.97349
7	300.00	120.00	8.00	15.00	0.01127	3.01721
8	450.00	120.00	8.00	15.00	0.05894	2.94798
9	300.00	30.00	4.00	30.00	0.01611	2.98211
10	450.00	30.00	4.00	30.00	0.00959	3.06281
11	300.00	120.00	4.00	30.00	0.01553	2.86827
12	450.00	120.00	4.00	30.00	0.01279	2.97887
13	300.00	30.00	8.00	30.00	0.01492	2.98966
14	450.00	30.00	8.00	30.00	0.01271	2.94657
15	300.00	120.00	8.00	30.00	0.01594	2.9707
16	450.00	120.00	8.00	30.00	0.05854	3.38688

The statistical significance of the developed factorial model was assessed using ANOVA. The results are presented in Table 4. The closeness of adjusted R^2 and predicted R^2 indicates that the factorial model developed is a good fit of the experimental data and has good predictive capability. The model was found to be statistically significant with an F-value of 15224.79 and a *p*-value of 0.0064, confirming that the selected processing and formulation variables have a significant effect on the dielectric loss of the fabricated composites. All four main variables, namely NaOH solution volume (A), soaking time (B), silica loading (C), and pineapple leaf fiber powder loading (D), were statistically significant ($p < 0.05$), representing the fact that every formulation and processing variable significantly contributed to the measured dielectric loss. Further, several two-variable, three-variable, and four-variable interaction terms were also significant, implying that the dielectric response was controlled by coupled interactions between the investigated variables rather than individual variables in isolation. These results give us the justification to interpret the interaction plots in Section 3.3 as follows.

The standardized Pareto chart in Figure 4 shows even more clearly the relative influence of the variables studied on the dielectric loss. The largest standard effect was soaking time (Variable B), followed by NaOH solution volume (Variable A) and silica loading (Variable C) among the main effects. More importantly, the interaction between NaOH solution volume and silica loading (AC) and the three-variable interaction of NaOH solution volume, soaking time and silica loading (ABC) were found to be greater than the Bonferroni significance limit. The efficiency of silica incorporation is clearly highly dependent on the alkaline treatment conditions and must therefore be assessed in conjunction with the processing parameters, and not as an independent formulation variable.

Table 4. ANOVA table for loss tangent.

Source	Sum of Squares	df	Mean Square	F-value	*p*-value	
Model	0.0037	14	0.0003	15224.79	0.0064	Significant
A-NaOH solution volume	0.0002	1	0.0002	14135.87	0.0054	
B-Soaking Time	0.0008	1	0.0008	46886.70	0.0029	
C-Silica loading	0.0002	1	0.0002	13251.26	0.0055	
D-Pineapple leaf fiber powder loading	0.0000	1	0.0000	863.24	0.0217	
AB	0.0004	1	0.0004	23909.38	0.0041	
AC	0.0008	1	0.0008	44031.53	0.0030	
BC	0.0004	1	0.0004	20620.45	0.0044	
BD	0.0000	1	0.0000	851.85	0.0218	
CD	0.0001	1	0.0001	4493.39	0.0095	
ABC	0.0007	1	0.0007	40159.40	0.0032	
ABD	0.0000	1	0.0000	869.73	0.0216	
ACD	8.279E-06	1	8.279E-06	475.01	0.0292	
BCD	9.952E- 06	1	9.952E- 06	570.99	0.0266	
ABCD	0.0000	1	0.0000	2028.32	0.0141	
Residual	1.743E-08	1	1.743E-08			
Cor Total	0.0037	15				

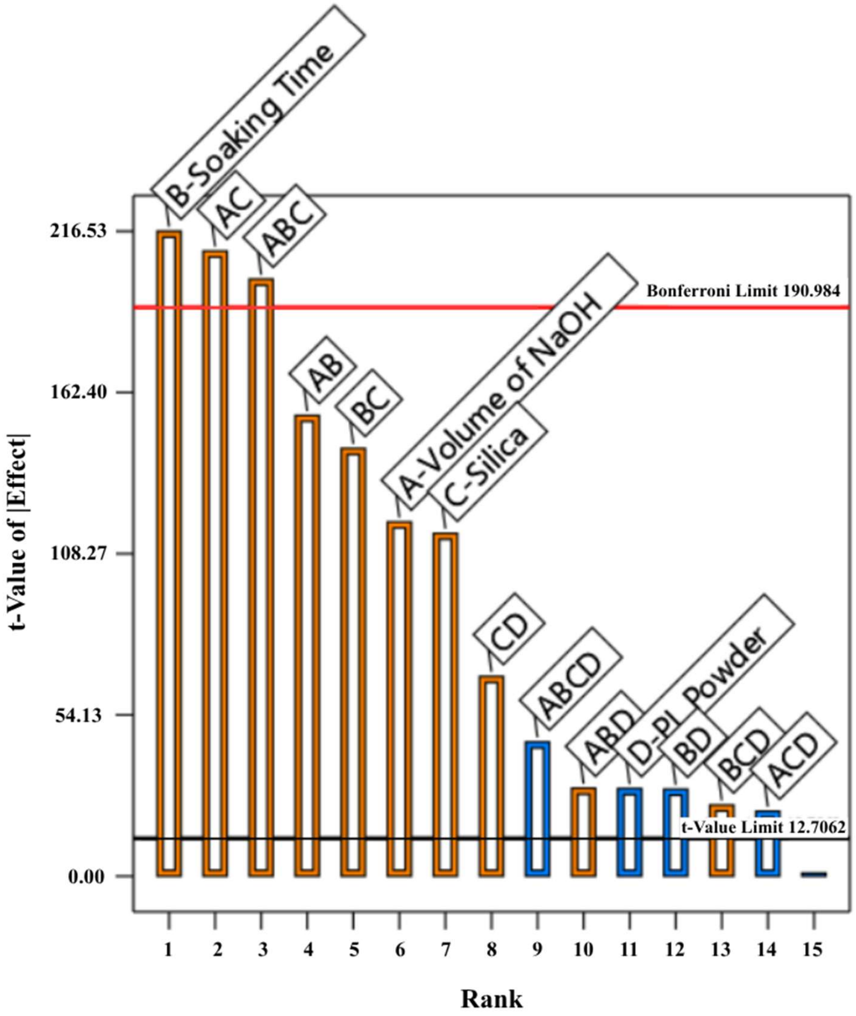


Figure 4. Standardized Pareto chart showing the significance of the investigated variables affecting dielectric loss

The interaction behaviour observed in the present study agrees with the previous reports on natural fiber composites, where alkaline treatment improves fiber-matrix interfacial compatibility while silica acts as a low-loss dielectric filler [14]. Factorial analysis revealed significant interaction effects, indicating that the reduction in dielectric loss is due to the combined effects of fiber treatment and silica incorporation rather than the contribution of either variable alone. This result highlights the importance of the simultaneous consideration of processing and formulation parameters in the design of bio-based dielectric composites for microwave applications.

Among the investigated formulations, the lowest loss tangent of 0.00959 was obtained by using 450 mL NaOH solution, 30 min soaking time, 4 g silica loading, and 30 g pineapple leaf fiber powder loading. This result suggests that the right combination of processing conditions and material composition is required to obtain low dielectric loss as compared to the higher loss tangent values observed in several other formulations. The developed factorial model offers a statistically reliable framework for evaluating the interaction effects of silica incorporation and processing parameters in pineapple leaf-epoxy composites.

3.2. Main Effects of Processing and Formulation Variables on Dielectric Loss

Figure 5 shows the main effects of volume of NaOH solution, soaking time, silica loading, and pineapple leaf fiber powder loading on the loss tangent of the formulated composites at 5 GHz. The main effect plots show the average effect of each variable on the dielectric loss by averaging the effect of other variables [13], [14]. Given the significant interaction effects in the ANOVA analysis, the trends depicted in Figure 6 should be considered along with the interaction effects presented in the following section.

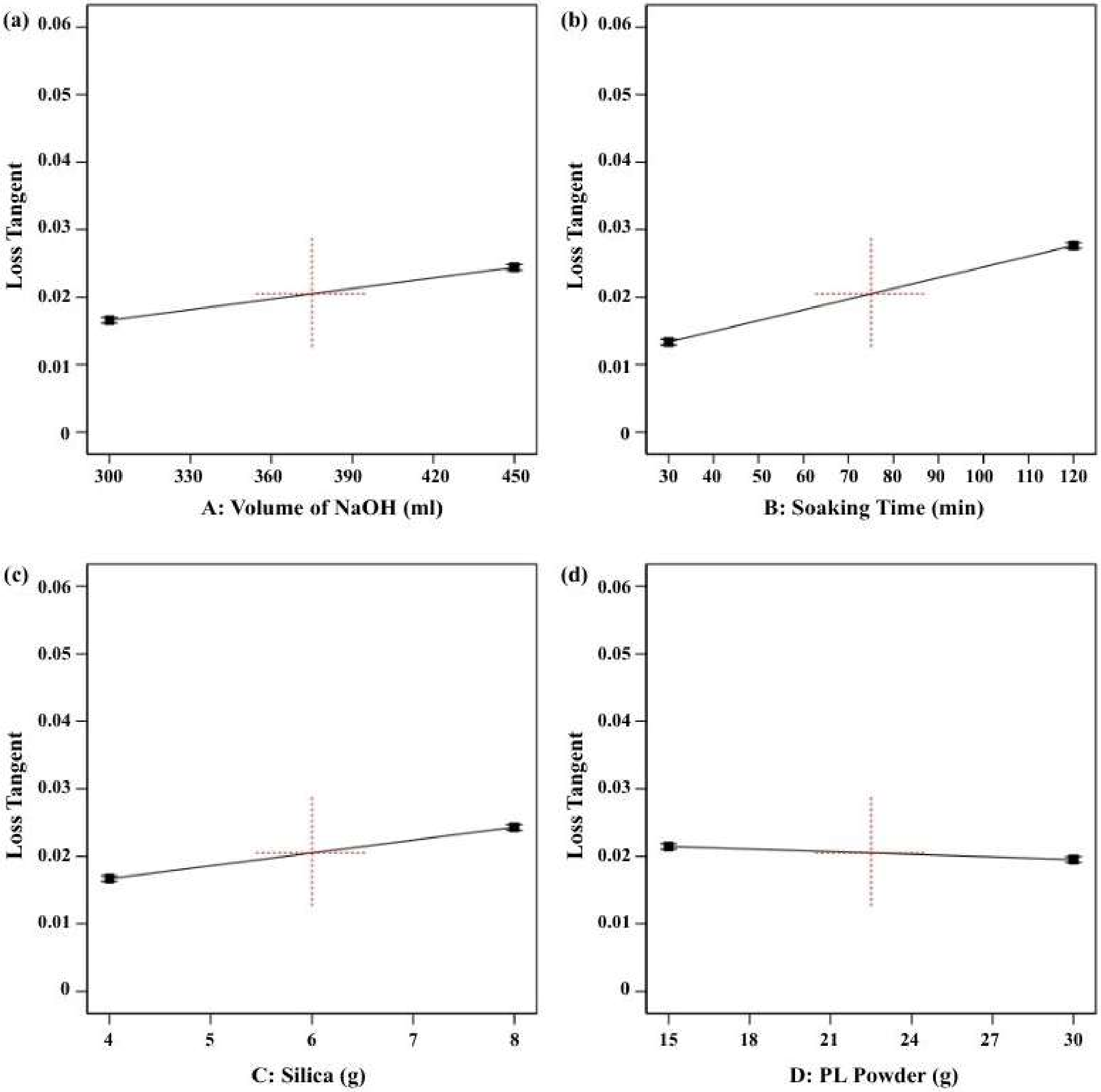


Figure 5. Main effect plots showing the influence of the investigated variables on loss tangent

As shown in Figure 5(a), the average loss tangent increased slightly as the NaOH solution volume increased from 300 mL to 450 mL. Similarly, Figure 5(b) shows that increasing the soaking time from 30 min to 120 min also increased the average loss tangent. These observations indicate that increasing the severity of alkaline treatment alone did not improve the dielectric performance within the experimental range investigated. Similar findings have been reported in previous studies, where the effectiveness of alkaline treatment was found to depend strongly on the selected treatment conditions. Excessive chemical treatment may damage the fiber structure or alter the fiber-matrix interface, resulting in deterioration of the dielectric properties of natural fiber composites [9,15].

The effect of silica loading is shown in Figure 5(c). The average loss tangent increased moderately with the increase in silica loading from 4 g to 8 g. While silica is a commonly used low-loss dielectric filler, the results presented here show that its performance is dependent on the processing conditions associated with it and not just on silica loading [15]. This apparent trend should not be analyzed in isolation, since the significant interaction effects detected in the factorial analysis indicate that the effect of silica loading depends on the chosen alkaline treatment conditions. Based on the interaction plots, the effect of silica addition is further discussed in Section 3.3.

It can be seen in Figure 5(d) that the average loss tangent slightly decreased when the pineapple leaf fiber powder loading was increased from 15 to 30 g. However, the magnitude of this effect was much smaller than that of processing parameters and silica loading, which agrees with the relatively lower contribution of Variable D in the Pareto chart. The main effect analysis confirms that the dielectric behavior of the fabricated composites cannot be fully explained by the individual variables. However, the statistically significant interaction effects reported in Section 3.1 suggest that the dielectric loss is governed by a combination of both processing conditions and material formulation. Therefore, a detailed discussion of these interaction effects is given in the corresponding section.

3.3. Interaction Effects between Processing Parameters

The interaction plots derived from the TLFA are presented in Figure 6. These plots illustrate the combined effect of processing and formulation variables on the dielectric loss of the fabricated composites. In contrast to the main effect plots discussed in Section 3.2, the interaction plots show that the effect of one variable depends on the level of the other variable. The non-parallel trends observed in the various interaction plots are in agreement with the ANOVA results, confirming that the dielectric behaviour of the composites is governed by the coupled interactions and not by the individual variables acting independently.

Figure 6(a) shows the relationship between the volume of NaOH solution and the soaking time. It is observed that loss tangent was slightly reduced by increasing the volume of NaOH solution from 300 to 450 mL at soaking time of 30 min. However, at a soak time of 120 min, the same increase in volume of NaOH solution resulted in a significant increase in dielectric loss. These opposite trends suggest that the effect of NaOH solution volume depends on the soaking time, and that the condition for the alkaline treatment should be adjusted as a combined process, not as individual parameters. This behaviour is consistent with the previous studies reporting that the efficiency of alkaline treatment is heavily dependent on the treatment conditions applied to natural fiber composite [17].

Figures 6(b) and 6(c) show interactions involving silica loading. The loss tangent was slightly decreased with increasing the NaOH solution volume at 4 g silica loading but was considerably increased at 8 g silica loading (Figure 6(b)). Figure 6(c) also shows that at 4 g silica loading, the loss tangent increased slightly when the soaking time increased from 30 min to 120 min, but it increased significantly at 8 g silica loading. The combined interaction patterns reveal that the efficacy of silica incorporation is highly dependent on the selection of alkaline treatment conditions. This result is also confirmed by the AC, BC and higher order interaction terms found to be statistically significant in the ANOVA analysis, indicating that silica loading should be optimized together with the processing parameters and should not be treated separately [16]. Similar behaviour has also been observed in natural fiber composites where the effectiveness of inorganic fillers depends on the fiber treatment conditions and the resulting composite structure.

The interactions with pineapple leaf fiber powder loading are depicted in Figures 6(d) and 6(e). Increasing the soaking time increased the loss tangent at both fiber loadings, but the increase was more pronounced at 30 g, as shown in Figure 6(d). Figure 6(e) shows that the loss tangent increased with increasing silica loading at both fiber loadings, but this increase was considerably smaller at the higher fiber loading of 30 g. These interaction trends show that the loading of pineapple leaf fiber powder modifies the effect of both processing conditions and silica incorporation on the dielectric response. Although the main effect of fiber loading was relatively small, the interaction with the other variables suggests that the material formulation should be evaluated as an integrated system rather than individual parameters alone.

The interaction analysis confirms that the dielectric response of the fabricated composites is governed by the combined influence of alkaline treatment conditions, silica loading and loading of pineapple leaf fiber powder. Particularly, the interactions with silica loading are the main result of the present study. The mere addition of silica does not ensure an improvement in the dielectric performance. Instead of this, low dielectric loss can be obtained by a proper combination of processing conditions and material formulation. These results are in line with the ANOVA and Pareto analyses shown in Section 3.1, where many two-variable and higher-order interaction terms were found to be statistically significant, confirming the use of the two-level factorial analysis for the evaluation of complex formulation effects in bio-based dielectric composites.

The factorial analysis successfully identified interaction effects, but the present study did not directly investigate the underlying microstructural mechanisms. Thus, the measured dielectric responses and the results reported in the literature are in agreement with the interpretations proposed. Future work could employ complementary characterization techniques (e.g. scanning electron microscopy (SEM), FTIR) to gain further insight into the relationship between fiber treatment, silica dispersion and dielectric performance.

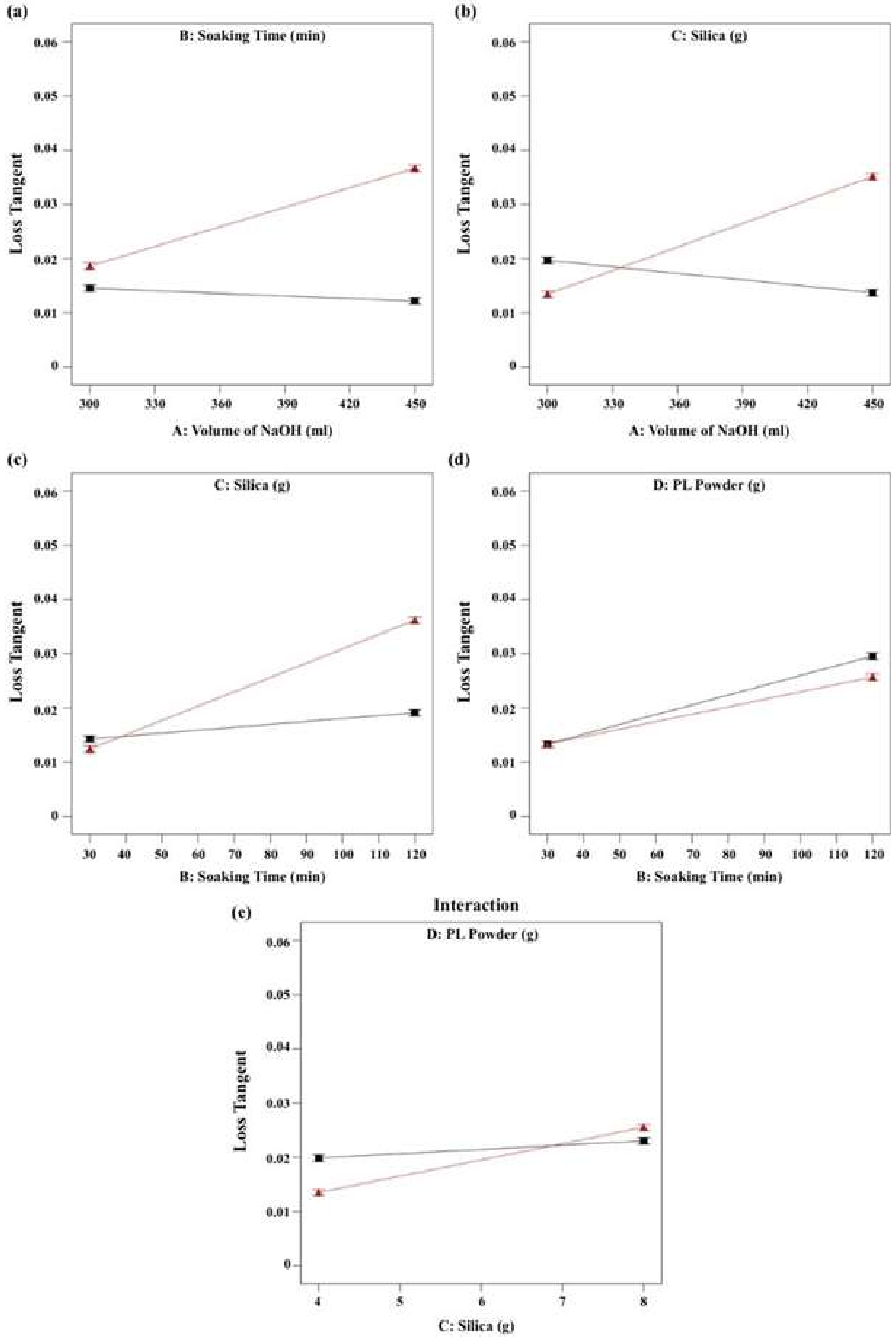


Figure 6. Interaction plots illustrating the combined influence of processing and formulation variables on loss tangent

3.4. Comparison with Previously Reported Pineapple-Based Dielectric Materials

Table 5 presents the dielectric performance of the formulated silica-modified pineapple leaf–epoxy composite in comparison with the reported values for previously developed pineapple-based dielectric materials. The comparison is meant to provide a broad benchmark rather than a direct quantitative assessment, as the reported results were obtained using different composite systems, fabrication approaches, and measurement configurations. However, it provides good insight into the progress made in improving the dielectric performance of pineapple-based composites for microwave applications. The loss tangent (0.00959) of the silica-modified pineapple leaf–epoxy composite formulated in the present study is found to be significantly lower than that of the pineapple leaf–epoxy composite reported earlier at the same operating frequency of 5 GHz (0.028) [5]. This corresponds to about a 66% reduction in dielectric loss, and it shows that the composite can obtain much improved dielectric performance by using alkaline treatment in combination with the incorporation of silica. The observed improvement is in agreement with the interaction effects observed in the two-level factorial analysis, indicating that the dielectric performance is governed by the interplay between processing conditions and material formulation rather than silica incorporation alone.

The potential of pineapple-based dielectric materials for microwave applications was also shown recently. For example, a bamboo-pineapple natural fiber substrate has been recently developed for wearable antenna applications with good dielectric characteristics and successful operation of the antenna [18]. These results confirm further the potential of pineapple-derived materials as sustainable dielectric substrates for high-frequency applications, albeit with a different material architecture and fabrication approach than the present study. These comparisons indicate a clear trend in the evolution of the pineapple-based dielectric materials. The present work has not only achieved a significantly lower dielectric loss than the previously reported pineapple leaf-epoxy composite but also developed a systematic methodology to optimize the dielectric performance through the combined effects of silica incorporation and processing parameters. The results constitute a useful basis for future development of sustainable low-loss dielectric materials for microwave substrate applications.

Table 5. Comparison of the dielectric loss tangent of the developed silica-modified pineapple leaf–epoxy composite with previously reported pineapple-based dielectric composites

Material	Frequency (GHz)	Loss tangent	Reference
Pineapple leaf–epoxy + silica	5.0	0.00959	Present study
Pineapple leaf composite	5.0	0.028	[5]
Bamboo–pineapple natural fiber substrate	See Ref.	0.015	[18]

4. Conclusions

The interaction effects of silica incorporation and processing parameters on the dielectric properties of pineapple leaf-epoxy composites at 5 GHz were investigated using two-level factorial analysis. The statistical analysis showed that the dielectric loss of the fabricated composites was significantly affected by the volume of NaOH solution, soaking time, silica loading, pineapple leaf fiber powder loading, and their interaction effects. The investigated formulations with 450 mL NaOH solution, 30 min soaking time, 4 g silica loading, and 30 g pineapple leaf fiber powder loading resulted in the lowest loss tangent of 0.00959. The interaction analysis also revealed that the dielectric performance could not be attributed to any single variable. However, the efficiency of the silica incorporation was conditioned by the selected alkaline treatment conditions, highlighting the importance of the simultaneous optimization of the processing conditions and formulation of the material for the design of low-loss bio-based dielectric composites. The developed silica-modified composite exhibited about 66% reduction in the dielectric loss compared to the previously reported pineapple leaf–epoxy composite tested at the same operating frequency, showing the effectiveness of combining alkaline treatment and silica incorporation. The results indicate that the silica-modified pineapple leaf-epoxy composites have great potential to be used as sustainable dielectric materials for microwave substrate applications. In the present work, formulation screening and dielectric characterization were carried out. Future work should include complementary microstructural characterization, mechanical and thermal performance evaluation, and device-level validation through antenna fabrication and testing to establish the relationship between the material structure and the dielectric performance, and to evaluate the suitability of the developed composite for practical microwave substrate applications.

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Declaration of Competing Interest

The authors declare no conflict of interest.

CRediT Authorship Contribution Statement

S. N. H. Zamri (Conceptualization; Methodology; Investigation; Writing – original draft)
M. A. M. Adzri (Methodology; Formal analysis; Data curation; Software; Visualisation)
H. Pratiwi (Validation; Resources; Writing – review & editing)
M. S. A. Karim (Validation; Resources; Writing – review & editing)
N. A. T. Yusof (Conceptualization; Supervision; Project administration; Funding acquisition; Writing – review & editing)

Availability of the Data and Materials

The data used to support the findings of this study are included within the article.

Ethical Declaration

This research did not involve any human participants, animals, or sensitive personal data. Therefore, ethical approval was not required. All data used in this study were obtained from publicly available sources and used in accordance with relevant guidelines and regulations.

Generative Artificial Intelligence Declarations

The authors used AI-based tools solely for language editing and grammar refinement. No content generation or data interpretation was performed by AI. All intellectual contributions are original and solely attributable to the authors.

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