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Tensile and Interfacial Performance of Epoxy Composites Reinforced with Alkali-Treated Kenaf Fibers

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Abstract

Natural fiber-reinforced composites are increasingly promoted as sustainable alternatives to synthetic materials in lightweight applications. This study evaluates the tensile properties of epoxy composites reinforced with long kenaf fibers (40–60 mm) treated with sodium hydroxide (NaOH). Composites containing 0%, 15%, 30%, and 45% fiber by weight were fabricated using the hand lay-up method and tested according to ASTM D3039. Morphological analysis was carried out using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDX). The composite with 45 wt% kenaf fibers treated with 5% NaOH showed the highest tensile strength (50.46 MPa) and strain (5.14%), with statistical significance confirmed by ANOVA ($p < 0.05$). In comparison, the 6% NaOH-treated composite at 30 wt% achieved the highest tensile modulus (1619.5 MPa). SEM observations indicated stronger fiber–matrix adhesion in the 5% NaOH group, while the 6% treatment caused fiber weakening and voids. EDX confirmed elemental changes on fiber surfaces after alkali treatment. Unlike many previous studies that mainly focused on short kenaf fibers and lower fiber loadings, this study examines the tensile and interfacial performance of long kenaf fibers (40–60 mm) at higher reinforcement levels up to 45 wt%. Overall, the findings indicate that moderate NaOH treatment, particularly 5% at higher fiber loadings, provides an optimal balance of strength and ductility. These results support the potential use of long kenaf fiber-reinforced epoxy composites in sustainable lightweight structural applications such as automotive and packaging components.

1. Introduction

Natural fiber-reinforced composites have emerged as sustainable alternatives to synthetic materials due to their biodegradability, availability, and reduced environmental footprint. Among various natural fibers, kenaf (Hibiscus cannabinus) is notable for its high strength-to-weight ratio, renewability, and potential for both structural and semi-structural applications [1], [2]. In Malaysia, kenaf has been actively promoted under national initiatives aimed at developing eco-friendly industries. These efforts focus on advancing the use of biodegradable

reinforcements such as kenaf and reducing reliance on petroleum-based materials in structural composites. Recent comprehensive reviews have reported increasing interest in natural fiber-reinforced epoxy systems due to their competitive mechanical performance, surface tunability, and environmental advantages [2]. Epoxy matrices are widely used in structural and semi-structural applications because of their high stiffness, dimensional stability, and strong interfacial bonding capability [3].

A major challenge in utilizing kenaf fibers in polymer composites is the incompatibility between the hydrophilic fiber surface and the hydrophobic epoxy matrix. This mismatch limits interfacial adhesion, reduces load transfer efficiency, and often leads to premature failure [4]. To address this issue, surface modifications such as alkaline (NaOH) treatment are commonly employed to remove surface impurities, including lignin, hemicellulose, and waxes, thereby enhancing fiber–matrix bonding [5], [6]. Alkali treatment enhances fiber surface roughness and wettability; however, excessive NaOH concentration may damage the fiber structure and reduce its integrity, particularly through disruption of the outer cell wall and partial cellulose degradation [7]. Similar observations have been reported in recent studies on alkali-treated kenaf/epoxy systems [7], [8].

Most previous studies have concentrated on short kenaf fibers (<30 mm) and relatively low fiber loadings (≤30 wt%), which provide limited understanding of the behavior of longer fibers at higher concentrations [9], [10]. Long fibers (40–60 mm), with their higher aspect ratio and reduced end discontinuity, are expected to improve stress transfer and load distribution, yet their use in epoxy composites remains underexplored [8], [11]. Although improvements in tensile properties have been reported for alkali-treated kenaf fibers, systematic evaluation of long kenaf fibers (40–60 mm) at high reinforcement levels (up to 45 wt%) remains limited. Furthermore, few studies correlate tensile performance with SEM and EDX analysis under high fiber loading conditions [9], [12], indicating a clear research gap in linking fiber length, alkali concentration, and interfacial behavior.

The concentration of NaOH also plays a critical role in balancing interfacial improvement with fiber integrity. A 5% NaOH treatment is typically sufficient to enhance surface roughness and wettability without severely compromising fiber strength [4], [5]. In contrast, higher concentrations such as 6% may increase bonding effectiveness but risk inducing fiber weakening or loss of ductility if not carefully controlled [7], [8]. Excessive alkali exposure may reduce interfacial stability due to fiber surface degradation and microstructural damage [7], [11].

In addition to tensile behavior, the interfacial performance of the composites is also important. Interfacial performance refers to the bonding quality between fiber and matrix, which governs stress transfer efficiency and overall mechanical properties. Strong fiber–matrix adhesion improves load distribution and reduces premature failure, whereas weak adhesion often leads to fiber pull-out and interfacial voids [7], [11].

This study therefore investigates the tensile and morphological properties of epoxy composites reinforced with long kenaf fibers treated with 5% and 6% NaOH at different fiber loadings (0%, 15%, 30%, and 45% by weight). Tensile testing was conducted according to ASTM D3039 standards, while microstructural features were analyzed using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDX). This study hypothesizes that a moderate NaOH concentration (5%) at higher fiber loading (45 wt%) can improve interfacial adhesion and stress transfer while maintaining ductility. In contrast, increasing the concentration to 6% may weaken the fiber structure and reduce mechanical performance. The aim is to identify optimal treatment conditions and fiber content that enhance mechanical performance without sacrificing ductility or interfacial quality.

2. Materials and Method

2.1 Materials

Raw kenaf fibers (40–60 mm) were obtained from a local supplier in Kelantan, Malaysia. Before chemical treatment, the fibers were manually cleaned to remove surface impurities, cut into uniform lengths, and stored in sealed containers to prevent moisture uptake. Sodium hydroxide (analytical grade) was used as the alkali treatment solution. The polymer matrix consisted of bisphenol-A epoxy resin and an amine hardener mixed at a 2:1 ratio [3]**.** Additional materials included plastic containers, stainless steel rods for fiber immersion, and pH indicator paper to monitor neutrality during rinsing. All weighing was performed using a calibrated electronic balance with a precision of ±0.01 g.

2.2 Chemical Treatment of Fibers

Kenaf fibers were immersed in 5% and 6% sodium hydroxide (NaOH) solutions (500 mL per 100 g of fiber) for 4 hours at room temperature. The alkaline solutions were prepared using distilled water. After treatment, the fibers were rinsed thoroughly with tap water to remove residual alkali and then washed with distilled water until a neutral pH (7) was confirmed using indicator strips.

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The fibers were first air-dried for 24 hours and then oven-dried at 60 °C for 6 hours to ensure complete moisture removal. This two-step drying method was adopted to minimize thermal degradation while maintaining consistent fiber quality. The treatment removed lignin, hemicellulose, and wax, thereby exposing cellulose fibrils. This improved fiber wettability and enhanced mechanical interlocking. Fig. 1 illustrates the treatment process, from the preparation of the NaOH solution to fiber immersion.

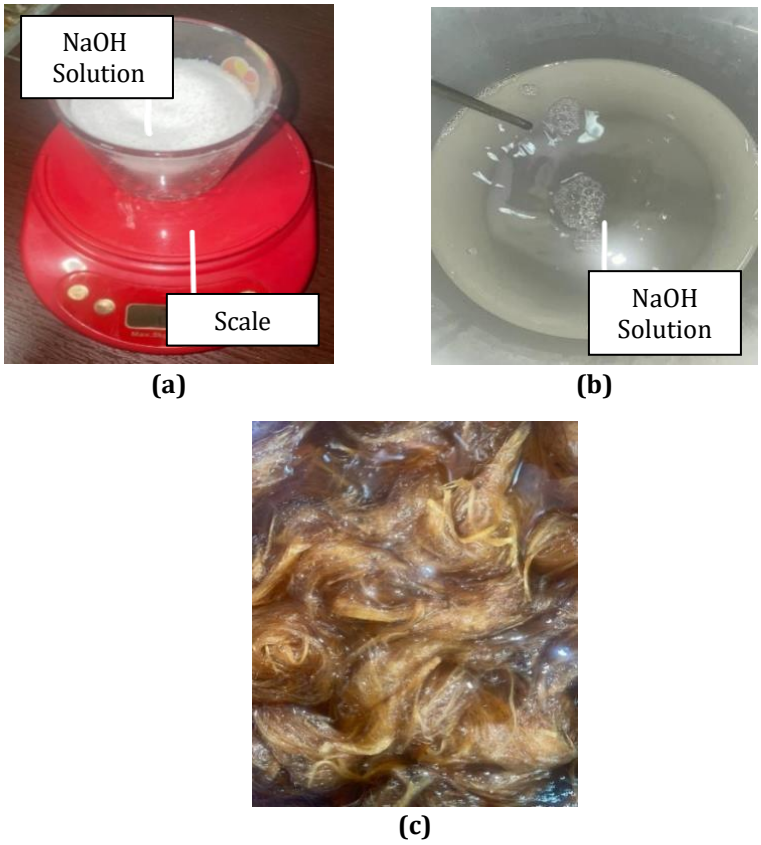

Fig. 1 *Chemical treatment process of fibers: (a) Weighing NaOH powder; (b) Dissolving NaOH powder; and (c) Immersing kenaf fibers in NaOH solution*

2.3 Composite Fabrication

Composites were fabricated using the hand lay-up technique with fiber loadings of 0%, 15%, 30%, and 45% by weight. The fiber–resin mixtures were poured into rectangular molds, compressed, and cured for 24 hours at room temperature [13]. The curing was conducted under normal laboratory ambient conditions. No additional post-curing treatment was applied after the initial 24-hour curing period. To ensure uniform fiber distribution and minimize voids, the layers were manually compressed and smoothed during lay-up. This method was adopted for its cost efficiency and suitability for low-volume composite production. Fig. 2 illustrates the fabrication process, including mold preparation, multiple mold setup, pouring of the fiber–resin mixture, applying weight for compaction, and the final cured composite samples.

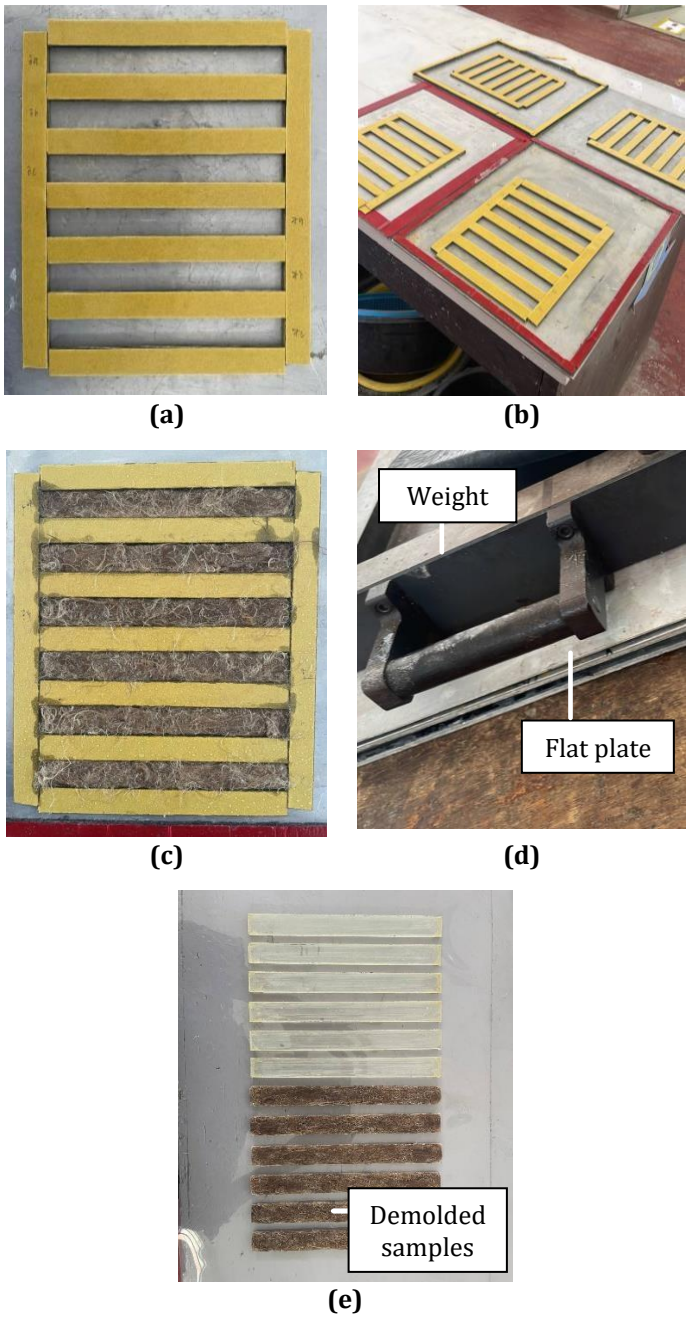

Fig. 2 *Composite fabrication process: (a) Mold preparation; (b) Multiple mold setup; (c) Pouring of the fiber–resin mixture; (d) Applying weight for compaction; and (e) Final composite samples*

2.4 Sample Characterization

2.4.1 Tensile Testing

Mechanical testing followed ASTM D3039 using a Universal Testing Machine (AGS-5KNJ, Japan) equipped with a precision extensometer (Fig. 3). Composite specimens were cut to standard dimensions of 165 mm × 20 mm × 3 mm. Testing was performed at room temperature, and each group was tested in triplicate to ensure statistical reliability, consistent with standard composite testing practices [14].

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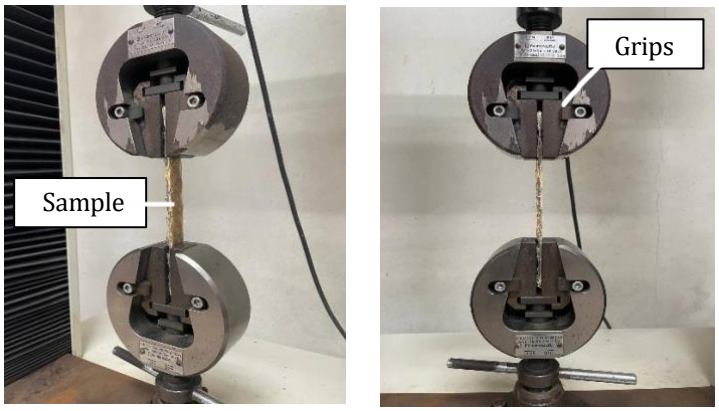
Fig. 3 *Universal testing machine* (*AGS-5KN, Japan)*

Stress–strain data were recorded in real time to determine tensile strength and modulus, allowing evaluation of composite performance under different fiber loadings and treatment conditions. In addition to quantitative measurements, the failure behavior of each specimen was visually observed and documented, including initiation points, crack propagation patterns, and fiber pull-out. These qualitative observations were used to correlate mechanical performance with microstructural features obtained from morphological analysis. This approach provided a deeper understanding of how interfacial bonding, fiber dispersion, and matrix integrity influence overall composite behavior. Fig. 4 shows the tensile testing setup used for mechanical property evaluation.



(a) **(b)**

Fig. 4 *Tensile testing setup*

2.4.2 Morphological Analysis

Fractured specimens from tensile testing were examined using a Scanning Electron Microscope (SEM; Hitachi SU1510) to assess fiber–matrix interaction, fracture characteristics, and failure modes [12]. SEM observations focused on interfacial voids, fiber pull-out, resin-rich regions and surface roughness. To ensure surface conductivity, the samples were sputter-coated with gold before imaging. The analysis complemented the mechanical results by visualizing bonding quality and fracture behavior under different treatment conditions. As shown in Fig. 5, sections of about 5 mm × 5 mm were cut from the fractured composites and prepared for SEM observation.

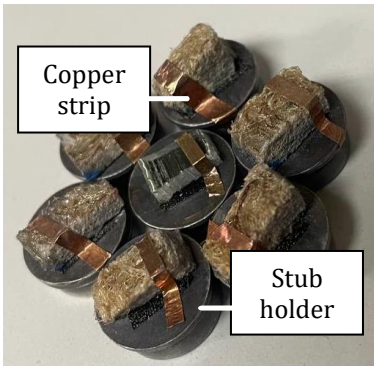


Fig. 5 *Small sections used for SEM and EDX testing*

2.4.3 Elemental Analysis (EDX)

Energy Dispersive X-ray Spectroscopy (EDX) was employed to characterize elemental distribution on treated fiber surfaces and fractured composite interfaces, consistent with previous SEM–EDX analyses in natural fiber composites [12]. Both elemental mapping and quantitative spectral analysis were used to identify major and trace elements, particularly carbon (C), oxygen (O), sodium (Na), and silicon (Si). EDX showed surface changes caused by NaOH treatment and detected inorganic residues or impurities. The analysis was performed using a Hitachi SU1510 scanning electron microscope, which was also used for the morphological study (Fig. 6).

Fig. 6 *Scanning electron microscope (SEM; Hitachi SU1510)*

2.4.4 Statistical Analysis

All tensile data (n = 3 for each group) were statistically evaluated using one-way Analysis of Variance (ANOVA) to test for significant differences between groups. Tukey's Honestly Significant Difference (HSD) post hoc test was applied for pairwise comparisons using Minitab software. A confidence level of 95% was adopted, and results with p-values below 0.05 were considered statistically significant. This approach ensured reliable validation of the experimental findings.

3. Results and Discussion

The experimental findings show the influence of fiber content and alkaline treatment on the tensile behavior and overall mechanical performance of the composites. The results are also compared with previous studies to support and contextualize the observed trends.

3.1 Tensile Properties

The tensile results showed clear differences across fiber contents and alkali treatment levels, consistent with earlier studies on natural fiber-reinforced composites [2], [9]. As shown in Table 1 and Fig. 7, the composite containing 45 wt% kenaf fibers treated with 5% NaOH recorded the highest tensile strength (50.46 MPa), and the difference was statistically significant (ANOVA, $p < 0.05$).

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This improvement is mainly due to better fiber–matrix adhesion from moderate alkali treatment, which removed surface impurities and roughened the fiber, allowing more effective stress transfer [2], [5], [8]. In contrast, composites treated with 6% NaOH showed a less consistent trend. Although tensile strength peaked at 45 wt% (46.60 MPa), it was still lower than that of the 5% group. The reduction in strength at 15% and 30% fiber content suggests over-treatment effects such as fiber degradation and poor dispersion, which can restrict stress transfer between fiber and matrix [8], [9], [11].

From a microstructural perspective, moderate alkali treatment (5% NaOH) removes amorphous components such as hemicellulose and partial lignin, resulting in greater exposure of crystalline cellulose fibrils and increased surface roughness [5], [7]. The exposure of cellulose enhances fiber surface reactivity and promotes stronger interfacial shear stress transfer between the kenaf fibers and the epoxy matrix. Recent studies on natural fiber–epoxy systems have shown that optimized alkali concentration improves interfacial bonding without significantly altering the crystalline cellulose backbone [7], [8]. This controlled surface modification enhances load transfer efficiency along the fiber axis, contributing to improved tensile strength at higher fiber loading.

In contrast, excessive alkali treatment (6% NaOH) may lead to partial disruption of the fiber cell wall structure and localized cellulose degradation, generating surface micro-defects and weakening intrinsic fiber strength [7], [8]. Such structural damage reduces interfacial shear strength and promotes premature debonding under tensile loading, which explains the lower tensile performance observed in the 6% treated composites.

Table 1 *Tensile strength (mean ± SD) and Tukey grouping*

NaOH concentration	Fiber content (%)			
	0% (Control)	15%	30%	45%
5% NaOH solution	36.58$^{a\ b}$ (±3.56)	24.64 ^{bc} (±6.34)	35.73$^{a\ b}$ (±8.52)	50.46^{a} (±0.27)
6% NaOH solution	36.58$^{a\ b}$ (±3.56)	19.19^{c} (±4.24)	29.50 ^{bc} (±6.96)	46.60^{a} (±3.90)

*Means with different letters indicate statistically significant differences (Tukey, $p < 0.05$). Values are presented as mean ± standard deviation.

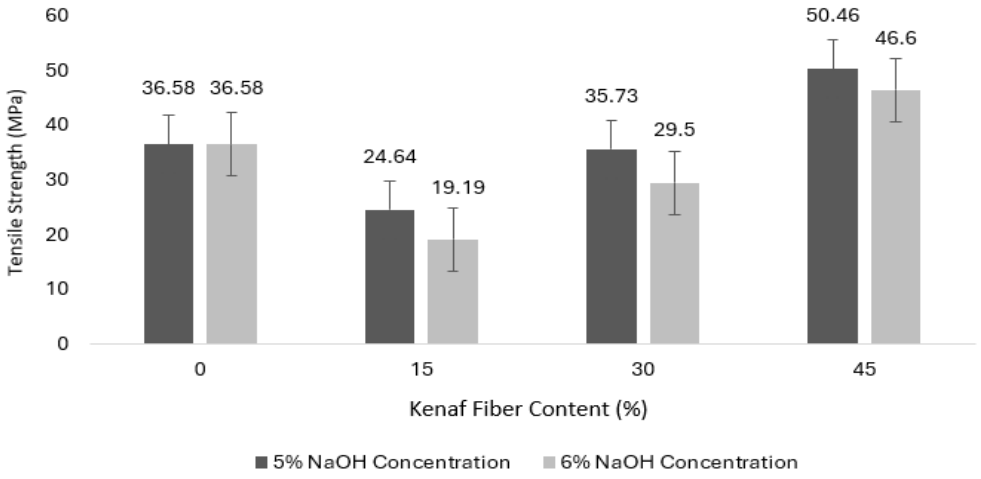

Fig. 7 *Tensile strength against kenaf fiber content*

Tensile modulus results (Table 2 and Fig. 8) revealed a different trend. The highest modulus (1619.5 MPa) was recorded at 30% fiber content for the 6% NaOH-treated sample. This indicates that a higher level of chemical activation may improve stiffness at moderate fiber content but does not necessarily enhance strength. The decline in modulus at 45% fiber content is likely due to fiber agglomeration or void formation within the matrix. For comparison, recent studies on alkali-treated kenaf/epoxy composites have reported tensile strength values typically ranging between 30–48 MPa depending on fiber length, treatment conditions, and reinforcement content [7] - [9]. The tensile strength of 50.46 MPa achieved in this study at 45 wt% fiber loading is comparable to or slightly higher than many reported values, indicating that the use of long kenaf fibers (40–60 mm) combined with optimized 5% NaOH treatment enhances stress transfer efficiency at high reinforcement levels.

Similarly, tensile modulus values in recent literature generally fall within the range of 900–1500 MPa for kenaf-reinforced epoxy systems [7], [9]. The modulus value of 1619.5 MPa obtained in this work lies at the upper range of reported data, demonstrating that alkali concentration and fiber content strongly influence stiffness performance.

Table 2 *Tensile modulus (mean ± SD) and Tukey grouping*

NaOH concentration	Fiber content (%)			
	0% (Control)	15%	30%	45%
5% NaOH solution	615.2^{d} (±54.5)	1115.4 ^{bc} (±152.1)	1254.3 ^{b} (±146.8)	989.5 ^{bc} (±82.7)
6% NaOH solution	615.2^{d} (±54.5)	869.3^{cd} (±49.6)	1619.5 ^{a} (±129.5)	1160.3 ^{bc} (±165.5)

*Means with different letters indicate statistically significant differences (Tukey, $p < 0.05$). Values are presented as mean ± standard deviation.

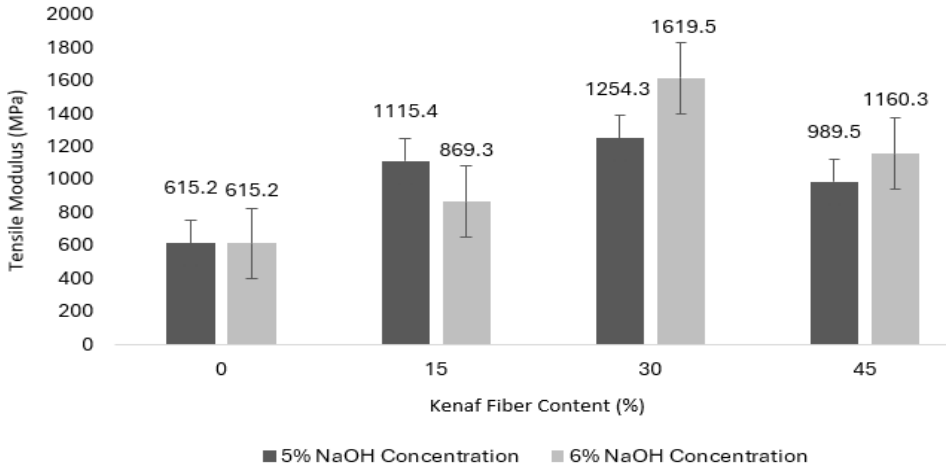

Fig. 8 *Tensile modulus against kenaf fiber content*

3.2 Stress and Strain

Stress–strain behavior (Table 3 and Fig. 9) followed the tensile strength trends and agreed with previous findings on other natural fiber composites [2], [9], [10], [16]. One-way ANOVA confirmed statistically significant differences among treatment groups and fiber loadings ($p < 0.05$). The 5% NaOH-treated composite with 45% fiber content showed the highest stress value at 53.12 MPa. In comparison, the 6% NaOH-treated sample reached a lower maximum of 49.05 MPa.

The improvement is mainly due to the removal of lignin, hemicellulose, and waxes at moderate alkali concentration. This treatment roughened the fiber surface and improved wettability [5], [15]. In contrast, treatment with 6% NaOH likely caused partial loss of ductility and surface damage, limiting load transfer and reducing ultimate stress. Similar effects from high alkali concentrations have been reported in earlier studies [9], [16].

Table 3 *Stress (mean ± SD) and Tukey grouping*

NaOH concentration	Fiber content (%)			
	0% (Control)	15%	30%	45%
5% NaOH solution	38.51$^{a\ b}$ (±3.74)	25.93 ^{bc} (±6.67)	37.61$^{a\ b}$ (±8.97)	53.12^{a} (±0.28)
6% NaOH solution	38.51$^{a\ b}$ (±3.74)	20.19^{c} (±4.46)	31.05 ^{bc} (±7.33)	49.05^{a} (±4.10)

*Means with different letters indicate statistically significant differences (Tukey, $p < 0.05$). Values are presented as mean ± standard deviation.

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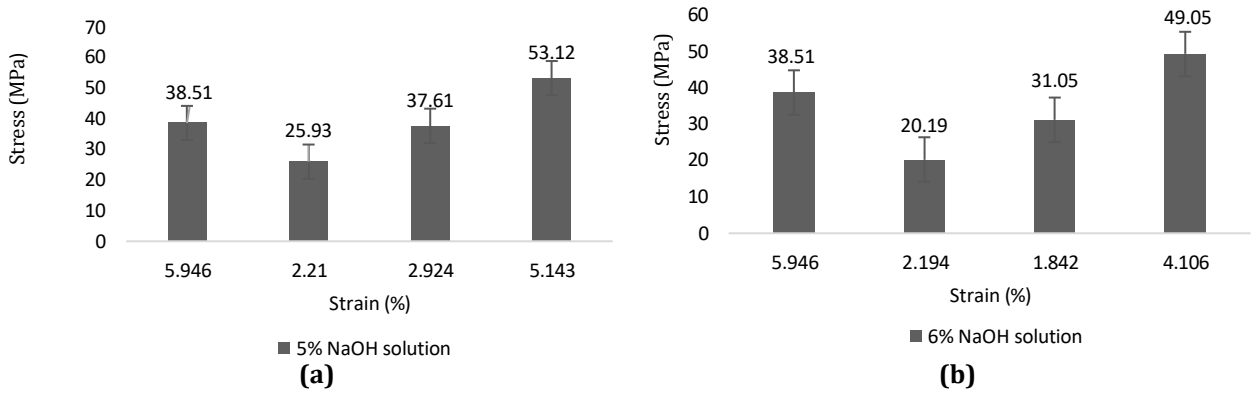

Fig. 9 *Comparison of stress against strain (a) Stress against strain graph for 5% NaOH solution; (b) Stress against strain graph for 6% NaOH solution*

Regarding strain behavior (Table 4), untreated samples showed the highest elongation (5.946%) due to matrix-dominated deformation in the absence of reinforcing fibers. The addition of fibers generally reduced strain in all composites because of increased stiffness. However, the 5% NaOH-treated composite at 45% fiber content retained relatively high strain (5.143%) while also achieving the highest stress. This shows that moderate NaOH treatment can balance stiffness and toughness [2], [8], [9]. The relatively high strain observed in the 5% NaOH-treated composite at 45 wt% fiber loading indicates that the fiber–matrix bonding was strong enough to reduce early fiber pull-out while still allowing gradual deformation of the composite. Improved interfacial shear strength enhances stress redistribution along the fiber length, allowing gradual crack propagation instead of sudden brittle fracture [7], [8]. This more stable stress transfer allows the composite to absorb more energy during tensile loading, resulting in a better balance between strength and ductility.

In contrast, the 6% NaOH treatment may cause surface damage and slight degradation of the fiber structure, which reduces the flexibility of the fibers [5], [7]. This weaker interface makes cracks form earlier and allows fibers to pull out more easily, which reduces the strain capacity and makes the composite behave more brittle.

Table 4 *Strain (mean ± SD) and Tukey grouping*

NaOH concentration	Fiber content (%)			
	0% (Control)	15%	30%	45%
5% NaOH solution	5.946^{a} (±0.109)	2.210^{d} (±0.535)	2.924^{cd} (±0.953)	5.143$^{a\ b}$ (±0.465)
6% NaOH solution	5.946^{a} (±0.109)	2.194^{d} (±0.361)	1.842^{d} (±0.504)	4.106 ^{bc} (±0.953)

*Means with different letters indicate statistically significant differences (Tukey, $p < 0.05$). Values are presented as mean ± standard deviation.

In contrast, the 6% NaOH-treated composites consistently exhibited lower strain values, with the lowest recorded at 30% fiber content (1.842%). This reduction indicates a loss of ductility and energy absorption, similar to over-treatment effects reported in other studies [9], [17].

Overall, these results confirm that 5% NaOH treatment is optimal, producing composites with a good balance of strength and strain capacity. ANOVA confirmed that these differences were linked to surface modification and fiber loading.

3.3 Scanning Electron Microscopy (SEM) Analysis

SEM observations revealed clear differences in fiber–matrix interfacial bonding between the 5% and 6% NaOH-treated composites (Fig. 10–12). The 5% NaOH-treated fibers showed rougher surfaces with visible fibrillation, leading to stronger mechanical interlocking and fewer interfacial voids. Less fiber pull-out was observed. Fracture surfaces showed a mixed cohesive–adhesive mode, reflecting strong adhesion. In contrast, the 6% NaOH-treated samples had smoother fiber surfaces with more evident fiber pull-out and interfacial gaps, suggesting weaker bonding caused by over-treatment and partial fiber damage. These observations are consistent with earlier reports. Moderate alkali treatment improves surface roughness and bonding, whereas higher concentrations reduce interfacial strength. Voids and resin-rich regions observed in the 6% samples act as stress concentrators, reducing structural integrity and fracture resistance [8], [9], [17].

The fibrillation observed in the 5% NaOH-treated fibers increases the effective surface area available for interaction with the epoxy matrix. This enhanced surface contact improves interfacial shear resistance and allows more uniform stress distribution along the fiber length [7], [8]. The roughened surface also promotes mechanical interlocking at the micro-scale, reducing the likelihood of premature debonding under tensile loading. As a result, crack propagation occurs in a more controlled manner, which explains the cohesive–adhesive fracture features observed in the 5% treated samples.

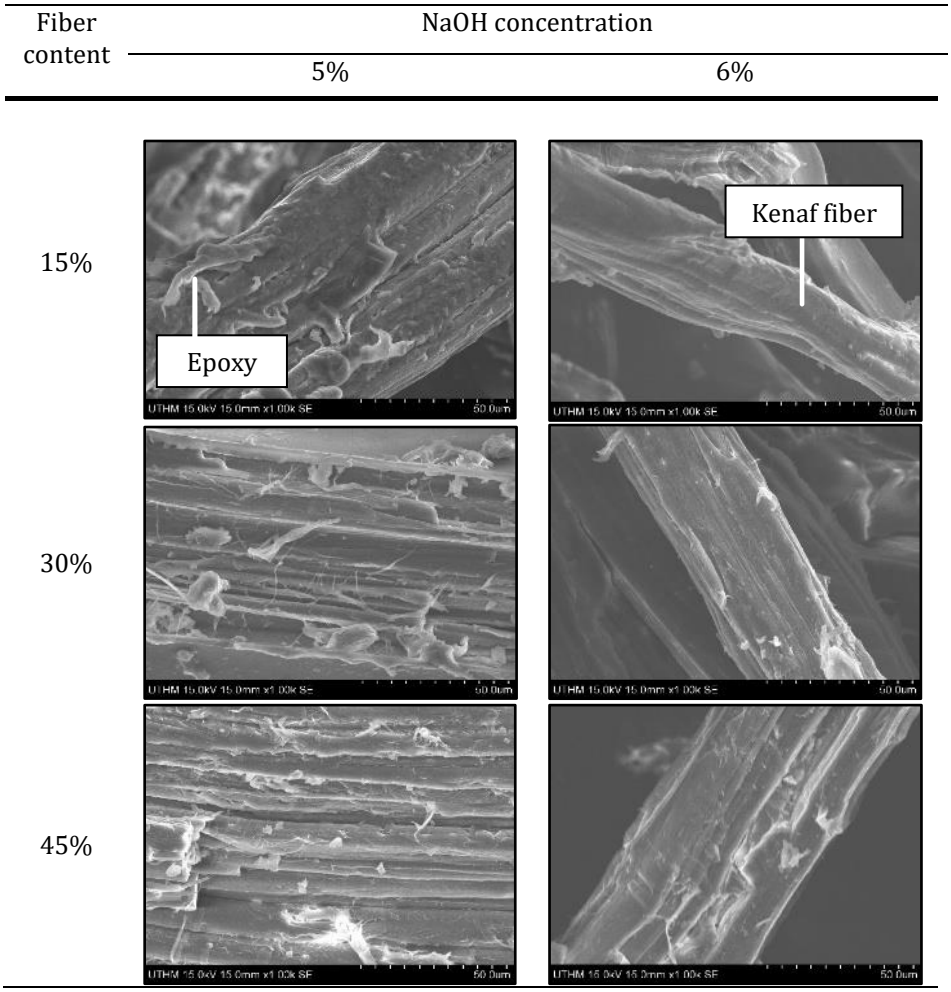

Fig. 10 *SEM micrographs of alkali-treated kenaf fiber/epoxy composites at different fiber contents (15%, 30%, and 45%) and NaOH concentrations (5% and 6%) viewed at 1000X magnification (scale bar = 50 μm)*

In the 5% NaOH-treated composites, the improved interface resulted from the removal of waxes, hemicellulose, and lignin. This process exposed cellulose fibrils and improved wettability, consistent with other natural fiber-reinforced composites [5], [8], [11]. Stronger bonding is essential for efficient stress transfer. This finding matches the superior tensile and stress–strain performance of the composites. Conversely, the micrographs of 6% NaOH-treated samples showed clean fiber pull-outs and resin-rich regions, indicating fiber–matrix debonding and limited load transfer, similar to results from other over-treated kenaf and natural fiber systems [9], [16]. Overall, the SEM observations are consistent with the tensile and stress–strain results. They confirm that 5% NaOH treatment gives the best surface condition for fiber–matrix adhesion, while higher concentrations tend to damage fiber integrity and weaken bonding.

In contrast, the smoother fiber surfaces and visible interfacial gaps in the 6% NaOH-treated samples indicate reduced interfacial shear strength and localized stress concentration. Excessive chemical treatment may weaken the outer cell wall layer of the fiber, creating surface defects that facilitate crack initiation and easier fiber pull-out [5], [7]. These microstructural changes limit effective load transfer between the fiber and matrix, leading to earlier debonding and reduced fracture resistance.

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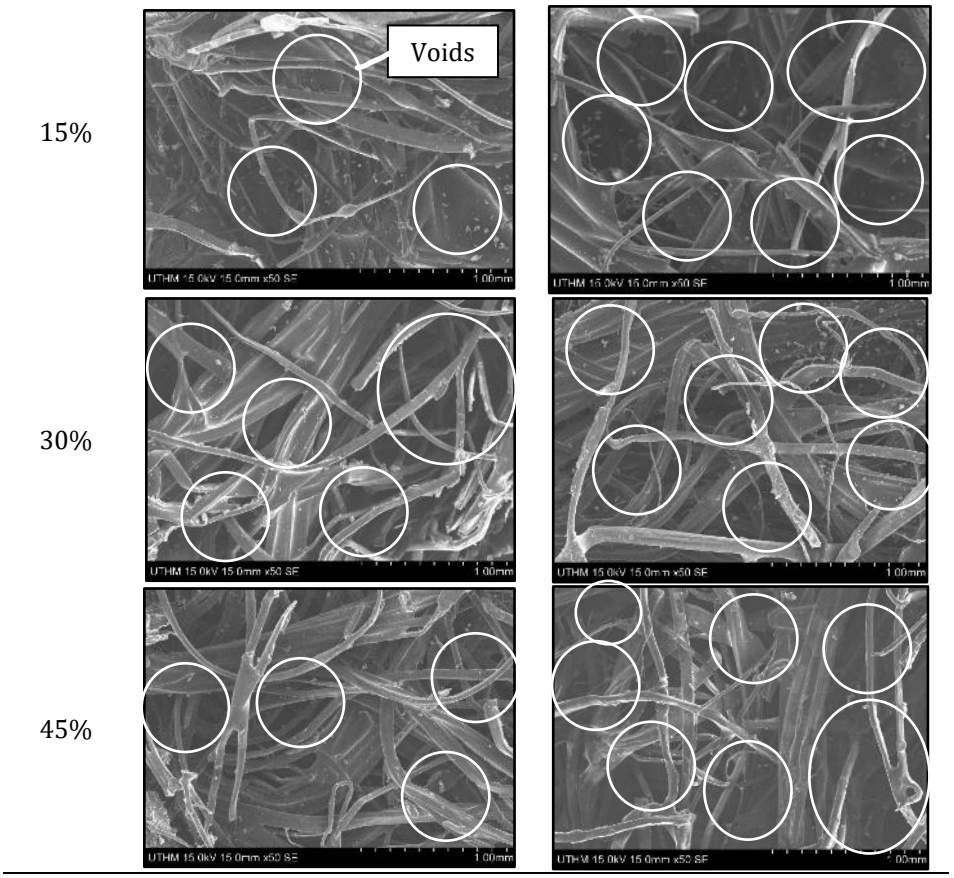
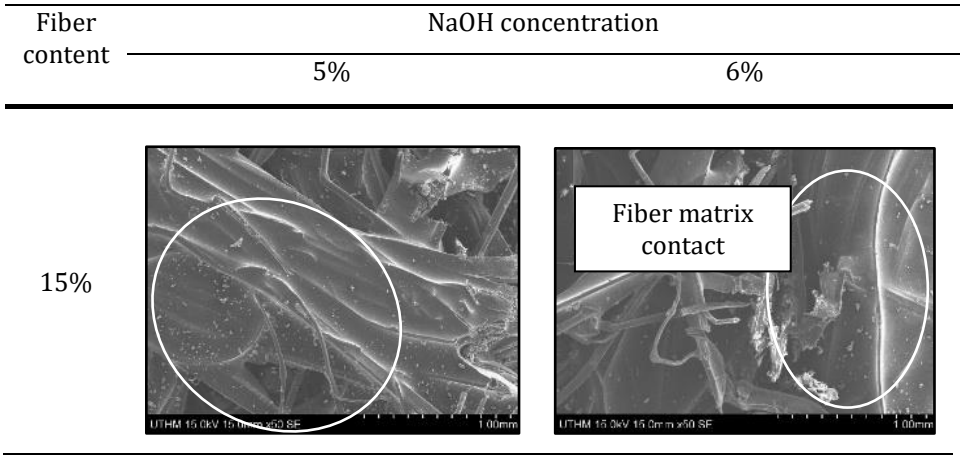


Fig. 11 *SEM micrographs of fiber dispersion and void distribution in alkali-treated kenaf fiber/epoxy composites at different fiber contents (15%, 30%, and 45%) and NaOH concentrations (5% and 6%) viewed at 50X magnification (scale bar = 1.00 mm)*



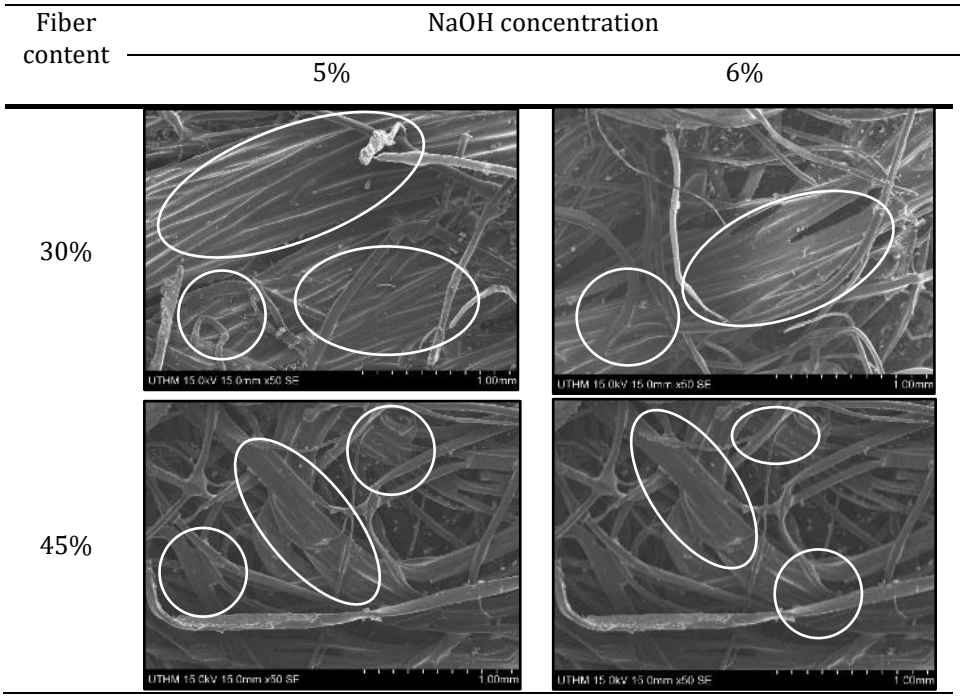


Fig. 12 *SEM micrographs of fiber–matrix interfacial contact in alkali-treated kenaf fiber/epoxy composites at different fiber contents (15%, 30%, and 45%) and NaOH concentrations (5% and 6%) viewed at 50X magnification (scale bar = 1.00 mm)*

3.4 Energy Dispersive X-ray Spectroscopy (EDX) Analysis

EDX was used to complement the SEM observations by giving quantitative elemental data on the surfaces of treated kenaf fibers and fractured composite regions. As summarized in Table 5, the 5% NaOH-treated samples showed a noticeably higher oxygen-to-carbon (O/C) ratio compared with the untreated and 6% NaOH-treated groups.

Table 5 *EDX element summary of selected samples*

Treatment	Key Elements	Remarks
5% NaOH	C, O, trace Na, Si	High O/C ratio, good adhesion
6% NaOH	C, O, higher Na	Residual Na, possible over-treatment

The higher O/C ratio reflects the removal of lignin, hemicellulose, waxes, and other hydrophobic substances, which exposed more cellulose fibrils. This surface exposure is important because it improves wettability and fiber–matrix adhesion. The increase in oxygen also suggests the presence of polar functional groups that promote hydrogen bonding and mechanical interlocking with the epoxy resin [5], [7], [8]. The increase in oxygen content suggests a higher concentration of polar functional groups on the fiber surface, which enhances chemical affinity with the epoxy matrix. Improved surface polarity facilitates stronger intermolecular interactions and contributes to higher interfacial shear resistance under tensile loading [7], [8]. In contrast, excessive alkali exposure may leave residual sodium and disrupt surface chemistry, which can interfere with optimal matrix cross-linking and reduce interfacial stability [7].

In addition to carbon and oxygen, the EDX spectra of the 5% NaOH-treated samples showed minor traces of sodium (Na) and silicon (Si). The sodium signal likely came from residual NaOH that was not completely removed, although its low intensity indicates effective rinsing and neutralization. The silicon may originate from natural mineral deposits in the fiber or from slight handling contamination, but its level was negligible. The low sodium content in the 5% treated samples suggests that the fibers retained their integrity and were not overexposed to chemical attack. These EDX findings are consistent with the SEM results, which showed rougher fiber surfaces, cleaner interfaces, and less fiber pull-out in the 5% group.

Conversely, the 6% NaOH-treated samples showed higher sodium content and a slightly lower O/C ratio, suggesting incomplete rinsing and possible over-treatment. Residual sodium on the fiber surface indicates that the rinsing process was incomplete. This residue may disrupt epoxy cross-linking or serve as stress initiation sites.

As a result, the 6% NaOH-treated composites showed reduced tensile performance and more brittle fracture behavior. Over-treatment at higher concentrations can cause cellulose degradation, loss of ductility, and weakening of the interfacial region. These effects were also visible in the SEM images, where the 6% samples displayed cleaner fiber pull-out and less cohesive failure.

Overall, the EDX analysis confirmed that moderate alkali treatment at 5% is more effective in improving fiber surface chemistry without compromising structural integrity. The resulting chemical modifications enhance compatibility between the hydrophilic kenaf fibers and the hydrophobic epoxy matrix. Similar results were observed in earlier studies [5], [8]. They found that optimal NaOH treatment improved surface reactivity and bonding, whereas higher concentrations led to fiber damage and reduced performance.

4. Conclusion

This study achieved its aim of evaluating the effect of NaOH treatment and fiber loading on the tensile and interfacial performance of long kenaf fiber-reinforced epoxy composites. Mechanical testing showed that both fiber content and alkali concentration significantly influenced tensile behavior, as confirmed by ANOVA. The composite with 45 wt% kenaf fibers treated with 5% NaOH recorded the highest tensile strength (50.46 MPa) and acceptable strain (5.143%), demonstrating superior stress transfer and a good balance of strength and ductility compared with the untreated and 6% NaOH-treated groups. In contrast, the 6% NaOH treatment improved stiffness at moderate fiber content but caused fiber weakening and greater void formation, which reduced overall strength and ductility. SEM results supported these findings by showing stronger fiber–matrix adhesion and fewer interfacial voids in the 5% NaOH-treated composites, while the 6% group displayed more fiber pull-out and interfacial debonding. EDX confirmed the removal of surface impurities and an increased oxygen content after 5% NaOH treatment, which enhanced wettability and bonding potential with the epoxy matrix. Overall, the results demonstrate that moderate NaOH treatment at 5% combined with higher fiber loading (45 wt%) provides the most effective balance of tensile performance and interfacial adhesion. These findings show that chemical surface treatment is a practical way to improve the performance of natural fiber composites in lightweight structural applications. Future studies can further examine the durability of these composites, particularly in terms of fatigue behavior, thermal performance, and water absorption under different service conditions. Further investigation on interfacial shear strength and dynamic loading behavior would help clarify their suitability for structural and semi-structural applications.

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Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm their contribution to the paper as follows: ***study conception and design****: Muhammad Afif Mohd Razali, Nor Mazlana Main;* ***data collection****: Muhammad Afif Mohd Razali;* ***analysis and interpretation of results****: Muhammad Afif Mohd Razali, Nor Mazlana Main;* ***draft manuscript preparation****: Muhammad Afif Mohd Razali, Nor Mazlana Main, Muhammad Arif Asyraf Mohd Zainuddin, Wafi Zulaikha Mohd Rozi, Noraini Marsi. All authors reviewed the results and approved the final version of the manuscript*

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