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Thermal, Structural and Biodegradability Properties of Bio-Based Kenaf/PMMA Composites Reinforced with Chitosan

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ABSTRACT

This study investigates the incorporation of chitosan into kenaf/poly(methyl methacrylate) (PMMA) hybrid composites to enhance thermal, physical, and biodegradability properties. Kenaf fibers were alkali-treated, ground, and mixed with PMMA, while chitosan was incorporated at 10 g and 20 g concentrations in PMMA. The composites were fabricated via hot pressing method and characterized using Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDX), Thermogravimetric Analysis (TGA), water absorption and soil burial analyses. FTIR spectra revealed intensified –OH and –NH stretching peaks (~3351 cm^{-1}), indicating strong hydrogen bonding and compatibility between chitosan and the PMMA matrix. SEM micrographs showed improved fiber–matrix adhesion with reduced void formation in the 20 g chitosan composite. TGA results demonstrated enhanced thermal stability, with char residue increasing from 1.43% (0 g chitosan) to 2.07% (20 g chitosan) and degradation temperatures shifting toward higher ranges. Water absorption tests showed a reduction of up to 28% in moisture uptake in chitosan-modified samples compared to the control. Soil burial analysis confirmed improved biodegradability, with weight loss increasing by nearly 35% after 30 days for the highest chitosan-loaded sample. EDX analysis further confirmed successful chitosan incorporation with increased oxygen and carbon elemental signals. Overall, chitosan significantly improved the interfacial bonding, thermal stability, durability, and environmental responsiveness of the kenaf/PMMA hybrid composites, making them viable candidates for sustainable applications such as biodegradable panels and green furniture.

Keywords: Bio-based Filler, Chitosan, Kenaf Fiber, PMMA Composite

INTRODUCTION

In recent years, the incorporation of bio-based fillers into polymer composites has gained increasing attention due to growing environmental concerns and the need to reduce dependency on petroleum-based materials (Salim & Sarmin *et al*., 2023). Natural fiber-reinforced composites, particularly those utilizing lignocellulosic fibers such as kenaf, jute, hemp, and flax, are widely studied for their biodegradability, renewability, and satisfactory mechanical properties (Salim & Sarmin, 2023; Salim *et al*., 2024; Sharma *et al*., 2025). However, the hydrophilic nature of these fibers and the incompatibility with hydrophobic polymer matrices like PMMA often result in poor interfacial adhesion, which affects the overall performance of the composites (Akil *et al*., 2011; Jawaid & Khalil, 2011).

Kenaf fiber has been extensively studied for composite reinforcement owing to its excellent strength-to-weight ratio, cost-effectiveness, and environmental benefits. Yet, its tendency to absorb moisture and degrade under humid or thermal conditions remains a challenge. To address this, various surface treatments, compatibilizers, and hybridization strategies have been explored (Bledzki & Gassan, 1999). For example, alkali treatment is a common method used to clean fiber surfaces and increase roughness for better matrix adhesion.

Poly(methyl methacrylate) (PMMA) is a widely used thermoplastic polymer known for its excellent optical clarity, good weather resistance, and ease of processing, which make it attractive in applications ranging from biomedical devices to automotive components (Kim *et al*., 2023; Lin *et al*., 2023). However, neat PMMA suffers from inherent drawbacks such as brittleness, relatively low impact strength, and limited thermal stability, restricting its broader utilization in high-performance or structural applications (Lin *et al*., 2023; Sosiati *et al*., 2022). To overcome these limitations, reinforcement with natural fibers or functional additives has been explored to enhance toughness, thermal resistance, and environmental performance.

Chitosan, a derivative of chitin, has gained attention as a valuable additive in this context. It possesses unique functional properties, including antimicrobial activity, biocompatibility, and excellent film-forming ability, which make it an ideal candidate for incorporation into polymer blends and bio-composites. A study by (Du *et al*., 2014) showed that adding chitosan to PLA composites improved moisture barrier properties and delayed the onset temperature of degradation (Ilyas *et al*., 2022) further reported that chitosan enhanced both thermal stability and mechanical strength when used as a coating agent on natural fibers in polyester matrices.

Studies by Ilyas *et al*. (2021) and Sarmin *et al*. (2023) have provided a foundational understanding of chitosan's interaction with different polymers. Chitosan's polar functional groups are capable of forming hydrogen bonds and even ionic interactions with certain matrix components, thus improving compatibility and interfacial adhesion. This interaction is particularly important in systems where the base polymer is non-polar, such as PMMA, and the reinforcement is polar, such as kenaf fiber.

This study contributes to the growing body of work on sustainable polymer composites by demonstrating that chitosan not only enhances the thermal and structural integrity of kenaf/PMMA composites but also accelerates biodegradability, offering a balanced pathway between durability and environmental responsibility. Unlike previous studies that examined chitosan primarily as a coating or barrier additive, our work integrates it directly into the composite matrix, showing its dual role as both a reinforcing and eco-functional filler.

A study by Akil *et al*. (2011) investigated the use of chitosan in kenaf/polypropylene composites and found that the incorporation of chitosan not only reduced water uptake but also improved tensile strength and thermal stability. However, research specifically focusing on chitosan’s role in kenaf/PMMA systems remains limited. Furthermore, investigations that link chitosan’s functional effects to biodegradability performance via soil burial testing are rare, despite their importance for sustainable material development.

Therefore, this study contributes to the current body of knowledge by exploring the combined effects of kenaf fiber and chitosan in a PMMA matrix, aiming to produce a composite that is both high-performing and environmentally responsible. The evaluation of thermal, morphological, and biodegradability characteristics provides new insights into the design of future green composite materials. This study contributes to the growing body of work on sustainable polymer composites by demonstrating that chitosan not only enhances the thermal and structural integrity of kenaf/PMMA composites but also accelerates biodegradability, offering a balanced pathway between durability and environmental responsibility.

METHODOLOGY

Preparation of Kenaf/PMMA/Chitosan Hybrid Composite

The main materials used in this work are kenaf fibers, Poly(methyl methacrylate) (PMMA), and chitosan. In this context, the kenaf fibers undergo alkaline treatment with 6% NaOH for six hours in room temperature to improve their properties through the effective removal of lignin and hemicellulose, which are elements in a fiber that may reduce its strength and compatibility with the polymer matrix. After treatment, the fibers were dried at 50 ºC in oven for 24 hours to remove the moisture. Finally, the materials were milled into powder form with size of 250 µm and mix properly with PMMA. The composite was prepared by thoroughly mixing the kenaf fiber powder (60 g) with PMMA (60

g) and adding 10 g and 20 g of chitosan to observe the effect on the properties of the composites. The formulation was selected based on previous study reporting effective reinforcement of bio-based composites with 10–20 wt.% chitosan (Ilyas *et al*., 2022), which demonstrated significant improvements in interfacial bonding and thermal stability and based on the preliminary trials in this study indicated that higher chitosan content beyond 20 wt.% led to poor dispersion and agglomeration. A composite without chitosan was also prepared as a control sample. The composition of the composites is shown in Table 1. Proper blending was necessary for uniform distribution of the materials to achieve maximum performance characteristics in the final product.

Table 1. Composition of the sample preparation

Sample	Kenaf powder (g)	PMMA powder (g)	Chitosan powder (g)
1	60	60	0
2	60	60	10
3	60	60	20

The hot press method was used to mold the composite samples once the materials were well mixed. This involved placing the blended mixture into a mold and applying heat for 100 °C and a pressure of 10 MPa for 15 minutes. Hot pressing is important, as it ensures better interfacial bonding of kenaf fiber with PMMA along with chitosan, which leads to good mechanical properties and good structural integrity of the final composite material. The hot-pressed samples were then allowed to cool and were subjected to various tests in order to study their physical, thermal, and biodegradability properties. This systematic approach in the preparation of materials ensures improved performance characteristics of the composites as in Figure 1.

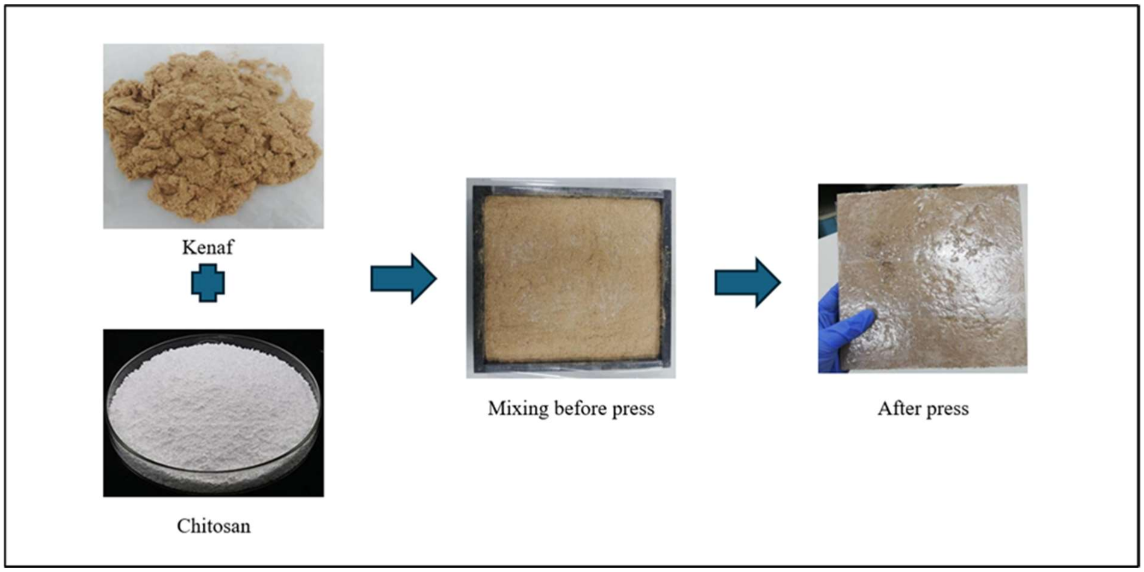


Figure 1. The process of making composites

Characterization and Testing of Properties of the Kenaf/PMMA/Chitosan Hybrid Composite

Water Absorption

The water absorption test was conducted with three replicate to assess the moisture resistance of the composites by measuring the amount of water absorbed over time. This test is crucial for understanding how well the composite can withstand humid environments, which is vital for its durability in practical applications (Sosiati *et al*., 2022). The water absorption percentage can be calculated using the formula Eq. (1):

$$Water\ Absorption\ (\%) = ((wf - wi)/wi) \times 100\% \quad \text{Eq. (1)}$$

Where *wf* is the final weight after immersion, and *wi* is the initial weight. Samples with the size of 50 mm × 50 mm × 3 mm were immersed in water at intervals of up to 24 hours, with absorption percentages calculated after each two hours.

Soil Burial Test

The soil burial test evaluated the degradation behavior of kenaf/PMMA/chitosan hybrid composites in natural soil conditions. Uniformly sized samples of 50 mm × 50 mm × 3 mm were oven-dried at 60 °C for 24 hours to remove moisture and weighed precisely. Prepared local soil area, free of debris, was used as the burial medium, with maintained moisture and a temperature of 25–30 °C to simulate real-life conditions (Samir *et al*., 2022). Samples were buried at a 40 mm depth, ensuring exposure to active microbial decomposition while preventing cross-contamination as in Figure 2. After 14 days, samples were retrieved, washed with distilled water, dried again, and reweighed. The extent of biodegradation was calculated using the formula Eq.(2):

$$Weight\ Loss\,(\%) \ = \ ((wo - wt)/wo) \times 100\% \qquad \text{Eq.(2)}$$

Where wo is the initial dry weight, and wt is the dry weight after burial. The weight loss reflected the material's degradation due to microbial activity.

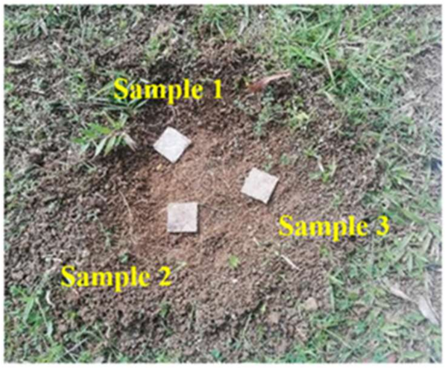


Figure 2. The position of samples for the soil burial test

Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) is a high-resolution imaging technique used to analyze the surface morphology, composition, and crystalline structure of materials. In this study, a Joel SEM was employed to examine the kenaf/PMMA/chitosan hybrid composite. Samples were coated with a thin layer of gold using a sputter coater to prevent electrostatic charging and placed in a vacuum chamber for imaging. SEM achieved magnifications ranging from a few times to hundreds of thousands, providing detailed insights into the microstructure. Coupled with Energy-Dispersive X-ray Spectroscopy (EDX), SEM enables elemental composition analysis by detecting characteristic X-rays emitted from the sample.

Thermogravimetric Analysis (TGA)

Thermogravimetric Analysis (TGA) is a technique used to evaluate a material's thermal behavior by measuring weight changes as a function of temperature. In this study, a Hitachi STA7000 analyzer was used to analyze the thermal stability of kenaf/PMMA hybrid composites with chitosan. Samples were heated from 30 to 700 °C at a rate of 10 °C/min under a 10 mL/min air flow, generating TGA curves that provided insights into decomposition temperatures, thermal stability, and volatile component content.

RESULTS AND DISCUSSION

Water Absorption

The water absorption characteristics of kenaf/PMMA hybrid composites with varying chitosan content were evaluated for 24 hours

(Figure 3). As expected, all samples showed a gradual increase in water absorption with time however, significant differences were observed in the overall absorption levels based on chitosan loading.

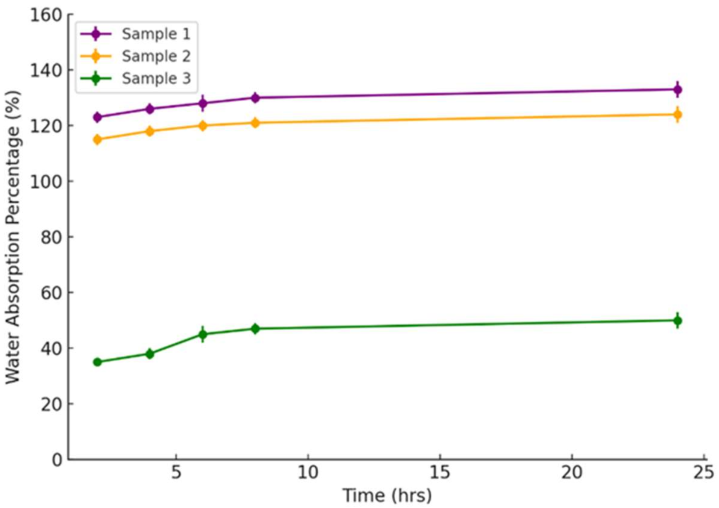


Figure 3. The graph shows the water absorption property of Kenaf/PMMA/Chitosan hybrid composite.

Sample 1, the control composite without chitosan, exhibited the highest water uptake, reaching approximately 135% after 24 hours. Sample 2, with 10 g of chitosan, showed a slightly reduced water absorption of about 130%, while Sample 3, with 20 g of chitosan, demonstrated a substantially lower absorption rate of around 52%.

This trend demonstrates the positive role of chitosan in mitigating water absorption. The observed reduction in water uptake with increasing chitosan content can be attributed to improved interfacial bonding between the kenaf fibers and the PMMA matrix. Chitosan, with its film-forming ability and reactive amine and hydroxyl groups, enhances the matrix–filler interface by filling micro-voids and reducing capillary pathways for water penetration. As supported by SEM analysis (Figure 5), the presence of chitosan contributed to a more compact and homogeneous morphology, which effectively minimized water ingress.

These findings are in agreement with prior studies. For instance, Srivastava *et al*. (2024) reported a similar reduction in water absorption in chitosan-reinforced bamboo fiber composites, attributing it to better fiber-matrix adhesion (Srivastava *et al*., 2024). Similarly, Ahmadzadeh *et al*. (2018) developed PLA/CNT/chitosan composite fibers using electrospinning. They found that low-content chitosan (~7 wt%) enhanced mechanical strength and water resistance. Furthermore, Ilyas *et al*. (2022) reported that chitosan incorporation can reduce porosity and micro-crack formation in fiber matrices, leading to improved barrier properties and delayed moisture ingress.

The current results reinforce these previous observations and provide additional evidence that chitosan acts not only as a bio-based filler but also as an effective compatibilizer. Its multifunctional role improves interfacial integrity, reduces fiber hydrophilicity, and imparts greater dimensional stability under humid or wet conditions.

Overall, the integration of chitosan, particularly at 20 g loading, significantly enhances the composite's water resistance, making it possible for outdoor or humid-environment applications. The reduction in water uptake without compromising biodegradability or other functional properties positions this material as a promising candidate in the field of sustainable biocomposites.

Soil Burial

The biodegradability of the kenaf/PMMA/Chitosan hybrid composites was assessed through a soil burial test, and the resulting weight loss percentages are presented in Figure 4. After a predetermined burial period, the results indicated a clear trend: increased chitosan content corresponded with greater weight loss, suggesting enhanced biodegradability.

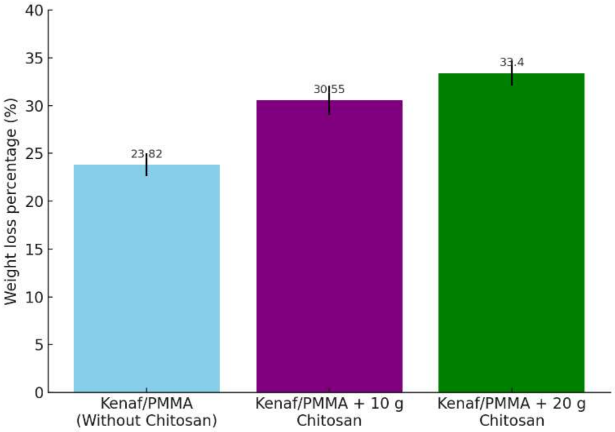


Figure 4. The graph shows the weight loss percentage of Kenaf/PMMA/Chitosan hybrid composite samples with different

The control sample exhibited a weight loss of 23.82%, whereas sample 2 with 10 g of chitosan showed a higher weight loss of 30.55%. The sample 3 with 20 g of chitosan recorded the highest degradation rate at 33.4%. This progressive increase in weight loss can be attributed to the biodegradable nature of chitosan, which enhances the overall microbial accessibility and degradation of the composite matrix when exposed to soil environments.

The results are in strong agreement with findings from Mokhothu & John, (2017) and Thomas *et al*. (2021), who reported that the incorporation of natural, biodegradable fillers such as starch, chitosan, and cellulose derivatives into synthetic polymer matrices significantly improved the degradation behavior of hybrid composites. In particular, Râpă *et al*. (2016) found that PLA-based composites containing chitosan experienced higher microbial colonization and structural breakdown during soil burial testing due to the biopolymer's susceptibility to enzymatic hydrolysis and microbial attack.

The enhancement in biodegradability is likely due to the increased hydrophilicity and availability of functional groups (–OH and –NH_2) introduced by chitosan, which promotes microbial adhesion and enzymatic activity. Furthermore, the improved dispersion and interfacial bonding between the kenaf fibers and PMMA matrix may have led to more uniform degradation, as voids and microcracks formed during degradation could propagate more readily in a compact composite structure containing chitosan.

Moreover, the increased weight loss of the chitosan-enhanced samples also reflects a shift in material balance toward more eco-friendly constituents. While PMMA is not inherently biodegradable, the synergistic effect of kenaf and chitosan which are both rich in cellulose and polysaccharides contributed to a composite system that is more susceptible to environmental degradation mechanisms.

These findings underscore the dual benefit of chitosan inclusion not only improves the composite's mechanical and barrier properties as shown in the water absorption and thermal tests, but it also advances the environmental degradability properties, aligning with the growing demand for sustainable materials. Such characteristics make the kenaf/PMMA/chitosan system a promising candidate for short-term or semi-durable applications where post-use degradation is desirable, such as in packaging, agricultural mulch films, or temporary construction panels.

Scanning Electron Microscopy (SEM) Analysis

Figure 5 presents SEM micrographs of the fracture surfaces of the kenaf/PMMA hybrid composites at 500x magnification. These images provide insight into the fiber–matrix interfacial morphology and the dispersion quality of chitosan within the composite system.

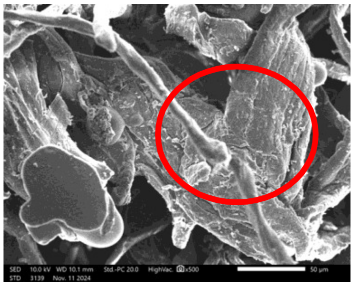
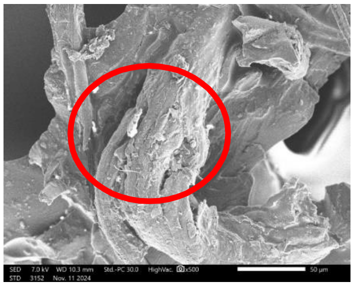
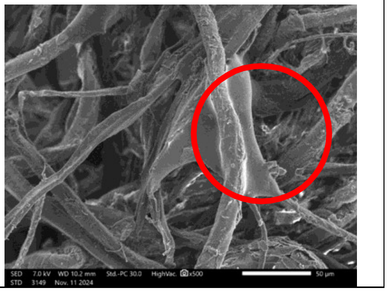
Kenaf/PMMA without chitosan	**Kenaf/PMMA + 10 g chitosan**	**Kenaf/PMMA + 20 g chitosan**
Sampel 1: 	Sample 2: 	Sample 3: 

Figure 5. The SEM images of Kenaf/PMMA/Chitosan hybrid composite samples at 500x magnification.

Sample 1 exhibits poor interfacial adhesion, as evidenced by the presence of noticeable voids, fiber pull-outs, and gaps between the kenaf fibers and the PMMA matrix. The absence of compatibilizing agent in this sample likely contributed to insufficient bonding, leading to weak stress transfer efficiency across the fiber–matrix interface. Such features are commonly associated with mechanical failure initiation and water permeation pathways.

In contrast, Sample 2 shows a marked improvement in surface morphology. The interface between the fiber and matrix appears more cohesive, with fewer visible voids and more embedded fibers, suggesting enhanced compatibility. The presence of chitosan likely improved wettability and interfacial interaction, forming a more integrated structure through hydrogen bonding and physical entanglement between the amine and hydroxyl groups of chitosan and the PMMA matrix.

Sample 3 demonstrates the most uniform and compact morphology. The fibers are well-encapsulated, and the surface appears smoother and denser, with minimal voids or discontinuities. This suggests that the higher chitosan content facilitated a more effective matrix-fiber network formation, reducing interfacial defects and enhancing structural integrity.

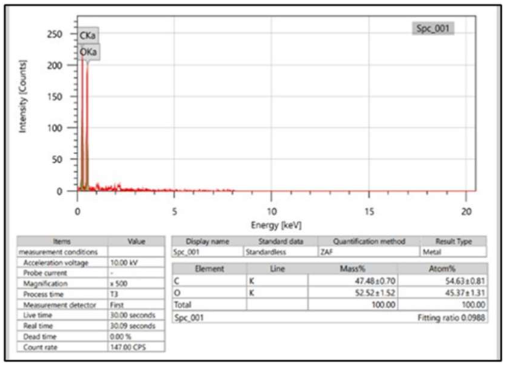
These observations are in agreement with prior studies by Popyrina *et al.* (2024) who reported that adding chitosan to natural fiber composites significantly reduced interfacial porosity and improved fiber adhesion. Similarly, Sarmin *et al.* (2023) observed that chitosan inclusion in jute fiber/epoxy composites enhanced fiber dispersion and matrix encapsulation, resulting in superior mechanical and water resistance properties. Moreover, Amaregouda *et al.* (2024) found that chitosan's ability to interact through hydrogen bonding contributed to the formation of a robust interface in starch-based biocomposites.

The enhanced fiber–matrix adhesion seen in chitosan-containing samples supports the improved performance noted in water absorption and thermal analysis. The reduction of microvoids not only limits water ingress but also delays the onset of degradation mechanisms under environmental exposure. Thus, SEM analysis confirms the crucial role of chitosan in improving the microstructural integrity of the kenaf/PMMA hybrid composites.

EDX Analysis

The Energy Dispersive X-ray (EDX) spectra of the composite samples, as shown in Figure 6, reveal the elemental compositions of the kenaf/PMMA composite without chitosan (Sample 1) and with 10 g chitosan (Sample 2). The primary elements detected were carbon (C) and oxygen (O), which are consistent with the organic nature of the matrix and reinforcing fiber components.

Sample 1 exhibited a carbon mass percentage of 47.48% and oxygen at 52.52%, indicating a relatively oxygen-rich environment due to the presence of hydroxyl groups from cellulose and PMMA's ester functionalities. In contrast, Sample 2 showed an increase in carbon content to 50.25% and a corresponding decrease in oxygen to 49.75%.

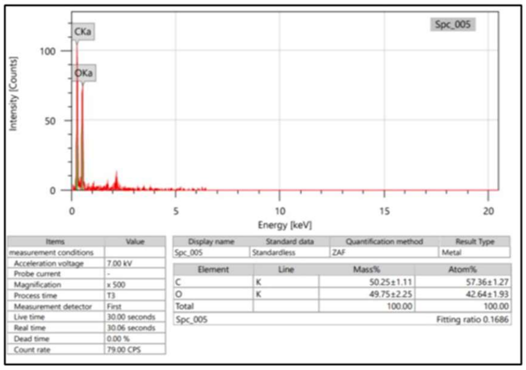


Items	Value
measurement conditions	
Acceleration voltage	10.00 kV
Probe current	-
Magnification	x 500
Process time	T3
Measurement detector	First
Live time	30.00 seconds
Real time	30.09 seconds
Dead time	0.00 %
Count rate	147.00 CPS

Display name	Standard data	Quantification method	Result Type
Spc_001	Standardless	ZAF	Metal

Element	Line	Mass%	Atom%
C	K	47.48±0.70	54.63±0.81
O	K	52.52±1.52	45.37±1.31
Total		100.00	100.00
Spc_001			Fitting ratio 0.0988

Sample 1

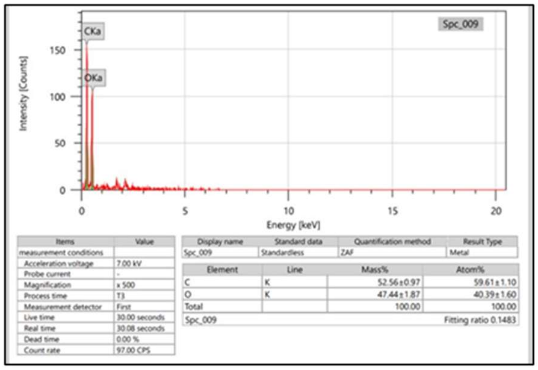


Items	Value
measurement conditions	
Acceleration voltage	7.00 kV
Probe current	-
Magnification	x 500
Process time	T3
Measurement detector	First
Live time	30.00 seconds
Real time	30.06 seconds
Dead time	0.00 %
Count rate	79.00 CPS

Display name	Standard data	Quantification method	Result Type
Spc_005	Standardless	ZAF	Metal

Element	Line	Mass%	Atom%
C	K	50.25±1.11	57.36±1.27
O	K	49.75±2.25	42.64±1.93
Total		100.00	100.00
Spc_005			Fitting ratio 0.1686

Sample 2



Items	Value
measurement conditions	
Acceleration voltage	7.00 kV
Probe current	-
Magnification	x 500
Process time	T3
Measurement detector	First
Live time	30.00 seconds
Real time	30.08 seconds
Dead time	0.00 %
Count rate	97.00 CPS

Display name	Standard data	Quantification method	Result Type
Spc_009	Standardless	ZAF	Metal

Element	Line	Mass%	Atom%
C	K	52.56±0.97	59.61±1.10
O	K	47.44±1.87	40.39±1.60
Total		100.00	100.00
Spc_009			Fitting ratio 0.1483

Sample 3

Figure 6. The energy spectra of Kenaf/PMMA/Chitosan hybrid composite samples at 500x magnification

This shift suggests the successful incorporation of chitosan into the composite matrix, as chitosan has a higher C:N ratio and a lower oxygen content compared to cellulose. The reduced oxygen percentage and enhanced carbon concentration in Sample 2 align with findings by Manyatshe *et al*. (2022), who reported similar elemental shifts upon the incorporation of chitosan into lignocellulosic matrices, attributing them to the partial substitution of hydroxyl groups with amino functionalities from chitosan (Manyatshe *et al*., 2022).

Moreover, the increased carbon content may also indicate improved compatibility and bonding between the chitosan and PMMA, enhancing the composite's homogeneity. This is in agreement with observations by Rajamuneeswaran *et al*. (2015), who emphasized the role of chitosan in improving the matrix-fiber interface due to its polar functional groups, which interact effectively with both the filler and polymer matrix (Rajamuneeswaran *et al*., 2015).

The fitting ratio values (0.0986 for Sample 1 and 0.1666 for Sample 2) further support the improved matrix-filler interaction in the presence of chitosan. A higher fitting ratio typically suggests a better signal-to-noise ratio and can be interpreted as a more homogeneous elemental distribution. Overall, the EDX results confirm the successful integration of chitosan into the kenaf/PMMA matrix and point to an enhanced interfacial interaction that likely contributes to improved composite properties, which will be further corroborated by SEM and thermal analysis results.

FTIR

The Fourier Transform Infrared Spectroscopy (FTIR) spectra of the kenaf/PMMA composites with and without chitosan (Figure 7) reveal significant insights into the chemical interactions between the matrix and filler components.

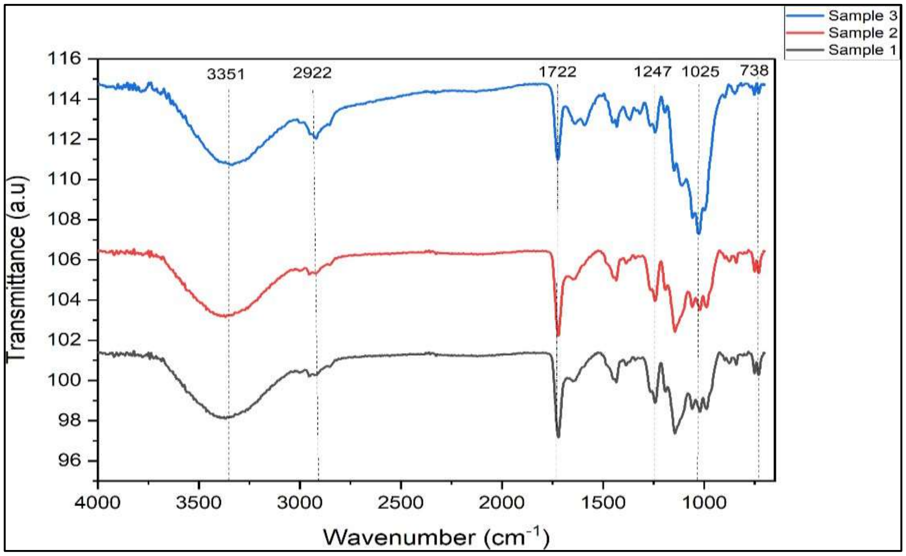


Figure 7. FTIR spectra of Kenaf/PMMA/Chitosan hybrid composite samples with varying amounts of chitosan (0, 10 g, and 20 g).

Characteristic absorption bands are observed at 3351, 2922, 1722, 1247, 1025, and 738 . The broad peak at 3351 cm^{-1} corresponds to the –OH and –NH stretching vibrations, typically associated with hydrogen bonding in hydroxyl and amine groups. This band becomes more intense and defined in Samples 2 and 3, suggesting the presence of chitosan, which is rich in hydroxyl and amino groups. This indicates enhanced hydrogen bonding interactions between chitosan and the kenaf/PMMA matrix. Similar results were reported by Wang *et al*. (2018), where the addition of chitosan to lignocellulosic matrices introduced stronger intermolecular bonding, as evidenced by amplified –OH bands (Wang *et al*., 2018).

The absorption at 2922 cm^{-1} is attributed to the aliphatic –CH stretching of the PMMA matrix and kenaf fibers. This band remains consistent across all samples, confirming the presence of the polymeric backbone and reinforcing fiber structures.

A strong peak at 1722 cm^{-1}, characteristic of C=O stretching in the ester group of PMMA, is observed in all samples. However, the slight shift and increased sharpness in Samples 2 and 3 suggest possible hydrogen bonding or dipole–dipole interactions between chitosan and the carbonyl groups of PMMA. This supports the hypothesis of chemical compatibility between the chitosan filler and PMMA matrix.

The bands at 1247 and 1025 cm^{-1} are associated with C–O–C stretching vibrations, indicative of PMMA and cellulose structure. These peaks become more prominent in chitosan-modified samples, further implying improved molecular interactions and potentially enhanced dispersion of chitosan within the matrix.

Finally, the 738 cm^{-1} band represents out-of-plane C–H bending, commonly associated with PMMA. This region does not show a major shift, but its relative intensity decreases in Samples 2 and 3, possibly due to the increasing dominance of chitosan's spectral features.

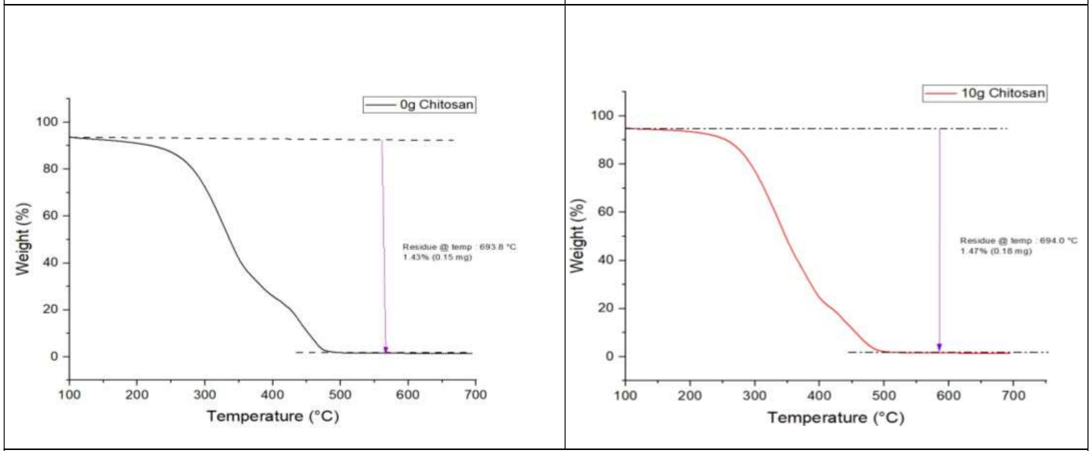
Overall, the FTIR results confirm that chitosan was successfully integrated into the kenaf/PMMA matrix, forming hydrogen bonds and possibly ionic interactions that enhance interfacial compatibility. These findings are consistent with the improved structural integrity observed in the SEM and EDX results. As noted by Rachtanapun *et al*. (2012), such interactions can significantly improve the mechanical, thermal, and barrier properties of bio-based composites.

TGA

The TGA curves (Figure 8) reveal the thermal degradation behavior over 100–700 °C and Table 2 shows the interpolated onset ($T_5\%$), maximum (T_max), and final ($T_{95}\%$) degradation temperatures together with the total weight loss and char residue for kenaf/PMMA/Chitosan hybrid composites.

Sample 1 (Kenaf/PMMA without chitosan) exhibited a two-step degradation pattern. The initial degradation temperature ($T_5\%$) occurred at approximately 250 °C, corresponding to the volatilization of low molecular weight compounds and hemicellulose decomposition. The maximum degradation temperature (T_max) was around 382 °C, associated with cellulose decomposition and PMMA backbone scission, followed by a final degradation temperature ($T_{95}\%$) near 480 °C. The overall weight loss reached 98.6%, leaving a char residue of 1.43% at 693.8 °C, indicating limited thermal resistance and char formation.

Upon incorporation of 10 g chitosan (Sample 2), the composite showed delayed degradation. The onset temperature shifted to ~280 °C, while T_max increased to 396 °C and the final degradation temperature was extended to 492 °C. The total weight loss was slightly reduced to 98.5%, with a char residue of 1.47% at 694.0 °C. This indicates that chitosan contributed to improved thermal resistance, attributed to its nitrogen content, which promotes char formation. These findings align with Hu *et al*. (2013), who demonstrated that chitosan-based flame retardants accelerate char yield and improve thermal stability in polymer systems.



Sample 1 (Kenaf/PMMA without chitosan)

Sample 2 (Kenaf/PMMA + 10 g chitosan)

Sample 3 (Kenaf/PMMA + 20 g chitosan)

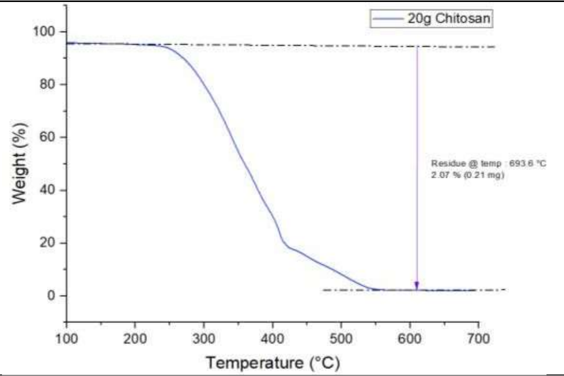


Figure 8. TGA curves of Kenaf/PMMA/Chitosan hybrid composite samples at different chitosan composition.

Table 2. The interpolated onset (T_{5}%), maximum (T_max), and final (T_{95}%) degradation temperatures together with the total weight loss and char residue for kenaf/PMMA/Chitosan hybrid composites.

Sample	Onset Temp T_{5}% (°C)	Maximum Temp T_max (°C)	Final Temp T_{95}% (°C)	Total Weight Loss (%)	Char Residue at 700 °C (%)
Sample 1	250	382	480	98.6	1.43
Sample 2	280	396	492	98.5	1.47
Sample 3	300	406	503	97.9	2.07

Sample 3 (20 g chitosan) showed the most significant improvement, with an onset temperature of ~300 °C, T_max at 406 °C, and a final degradation temperature of ~503 °C. The total weight loss was reduced to 97.9%, leaving a char residue of 2.07% at 693.6 °C. The increased residue confirms enhanced carbonaceous char yield with higher chitosan loading, consistent with the role of nitrogenous groups in catalyzing char formation. Similar effects have been reported by Wang *et al.* (2018) in lignocellulose–chitosan composites, where interfacial bonding and nitrogen-induced char formation improved thermal stability and dimensional integrity.

The improved thermal stability observed in Samples 2 and 3 can also be attributed to stronger interfacial interactions between chitosan and the polymer matrix, as supported by FTIR analysis. The formation of hydrogen bonds and possible ionic interactions between amino groups in chitosan and ester groups in PMMA restrict chain mobility, thereby delaying thermal chain scission and raising decomposition onset temperatures (Grząbka-Zasadzińska *et al*., 2017).

In summary, interpolation of the TGA data confirms that chitosan incorporation systematically increases the onset, maximum, and final degradation temperatures while reducing overall weight loss and increasing char residue. These results demonstrate that chitosan not only reinforces interfacial adhesion but also acts as a thermal stabilizer through its char-promoting effect, making kenaf/PMMA–chitosan composites more resistant to high-temperature degradation.

CONCLUSION

This study successfully demonstrated the incorporation of chitosan as a bio-based filler into kenaf/PMMA hybrid composites to enhance their thermal, physical, and environmental properties. The primary objective was to evaluate the effect of chitosan addition on interfacial bonding, thermal stability, water resistance, and biodegradability. The elemental analysis via EDX confirmed the homogeneous dispersion and interaction of chitosan within the kenaf/PMMA matrix, as evidenced by increased carbon and oxygen content correlating with chitosan incorporation. FTIR analysis further revealed the formation of hydrogen bonding and potential ionic interactions between the functional groups of chitosan and PMMA, indicating good interfacial compatibility and chemical integration. Thermal analysis by TGA demonstrated that chitosan addition significantly enhanced the thermal stability of the composites. An increase in char residue and a shift in degradation temperatures were observed with higher chitosan content, supporting its role in thermal resistance improvement due to its nitrogen-rich structure that promotes char formation. Chitosan also contributed to reduced water absorption, attributed to its semi-crystalline structure and compatibility with the PMMA matrix, which limited water ingress. This suggests improved durability and potential for application in humid environments. Moreover, soil burial tests confirmed increased biodegradability with chitosan addition, aligning with the environmental objective of developing a more eco-friendly composite. While the present work demonstrates significant improvements in thermal stability, interfacial bonding, and biodegradability, mechanical properties such as tensile, flexural, and impact strength were not evaluated. These are essential parameters for assessing practical applicability of bio-based composites. Future work will focus on systematically investigating the mechanical performance of kenaf/PMMA/Chitosan hybrid composites to complement the current findings and provide a more comprehensive understanding of their application potential

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