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Enhancing the Mechanical and Thermal Properties of Pine Wood Using Nanocomposite Reinforcement for Advanced Application

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ABSTRACT
Wood has been a necessity of society as the source of energy production, buildings, and furniture since the inception of human civilizations. To enhance the performance of furniture and building components for application under humid environments, wood has been subjected to modification through reinforcing the polymeric fillers over the decades. The present investigation deals with modification in mechanical and thermal properties of pine wood (PW). Modification of the properties of WPC over untreated wood was evaluated in terms of FTIR and simultaneous differential thermogravimetry-thermogravimetric-differential thermal analysis (DTG-TG-DTA) in air. The study concludes that incorporating nanomaterials into pine wood significantly enhances its mechanical strength and thermal stability, making it more durable and suitable for demanding environments. FTIR analysis confirms adequate bonding between nanomaterials and wood, while TGA results demonstrate improved resistance to thermal degradation, with slower decomposition and reduced mass loss at high temperatures. Additionally, AIBN nanofluid enables complete thermal degradation, leaving minimal residue and making the modified wood suitable for applications requiring full combustion or breakdown. These findings highlight the potential of nanomaterial-treated wood as a high-performance material for construction and other applications in humid or thermally intense environments.
Keywords: FTIR, TGA, Pinewood, AIBN (Azobisisobutyronitrile). Thermal stability.

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I. Introduction:

As the demand for eco-friendly and durable building materials continues to rise, the role of WPC in the construction industry is set to expand. Architects and builders are increasingly recognizing the benefits of WPC, not only for its performance characteristics but also for its contribution to sustainable building practices. WPC's versatility allows for creative and innovative design solutions, enabling the construction of aesthetically pleasing structures and functionally superior.

Polymer-reinforced wood plastic composites are revolutionizing the furniture and construction industries by offering materials that combine the best qualities of wood and plastic. Their durability, sustainability, and versatility make them ideal for various applications, from stylish and long-lasting furniture to robust, eco-friendly building components. As industries continue to prioritize sustainability and innovation, the prominence of WPC is likely to g 3row, driving a shift towards more resilient and environmentally responsible practices.

The growing demand for sustainable construction materials has renewed interest in wood as an eco-friendly alternative to synthetic materials like steel and concrete. However, to fully realize the potential of wood in modern construction, there is a need to address its inherent limitations. The advancement of nanotechnology presents a unique opportunity to enhance wood's mechanical properties in previously unattainable ways. Nanotechnology involves manipulating materials at the atomic or molecular scale, where they exhibit unique properties not present at larger scales. This approach allows for the development of new materials and the enhancement of existing ones, offering solutions to the challenges posed by traditional materials.

Nanotechnology has already demonstrated its potential in various fields, including medicine, electronics, and materials science. Nanomaterials have been used in construction to enhance the properties of concrete, steel, and other building materials, resulting in improved strength, durability, and functionality. However, the application of nanotechnology to wood is still in its early stages, and there is significant potential for further research and development. Incorporating nanomaterials into wood can enhance its mechanical strength, resistance to environmental factors, and overall performance, making it a more viable option for a wider range of construction applications.

For human society to grow, wood is an essential biological structural substance. Wood pulp fiber, tar, and charcoal are all made from wood, the raw chemical ingredient. Wood's strong strength-to-weight ratio, environmental friendliness, biodegradability, and aesthetic qualities make it a popular choice for building materials (Jang & Li, 2015). The following issues affect wood during processing and use: dimensional instability, fungal growth, UV rays, fire, and warping caused by moisture. The primary objective of wood modification was to tackle these issues(Zelinka et al., 2022).

The phrase "chemical modification of wood" became popular at this point. The chemical modification of wood is defined as the formation of covalent bonds between the modification agent and a reactive section of the cell wall components [3]. Wood

Table 1: Properties of the Nanomaterials

Nanomaterial Used	Property Improved	Advantages	References
nano-elulsion	Water absorption	When nanomaterials are impregnated, the amount of pore space and pore size inside the cell wall available for water molecule absorption decreases, producing a rough hydrophobic surface.	(Bansal & Pandey, 2023; Cao et al., 2023; Cui et al., 2023; Ge-Zhang et al., 2023; Harandi & Moradienayat, 2023; He et al., 2023; Liu et al., 2023; F. Wang et al., 2022; Yi et al., 2023; Q. Zhang et al., 2023; Zhao et al., 2023; Zheng et al., 2023)
acrylate nanoparticles			
nano silica, MWCNT			
spherical metal oxide			
SiO_2 , ZnO, TiO_2			
AgNPs			
CuO			
TiO_2, CeO_2	UV-protection	The coating shields the wood surface from sun damage by absorbing its rays. Because UV absorbers are much smaller than other absorbers, they can be added in higher concentrations without changing the coating's transparency.	(Bansal et al., 2022; Dong et al., 2017; Harandi & Moradienayat, 2023; Pescuma et al., 2023; Salla et al., 2012; Tanwar & Kaur, 2022; F. Wang et al., 2022; Z. Wang et al., 2020; Zhou et al., 2023)
SiO_2 , ZnO			
nano silica,			
acrylate nanoparticles			

ZnO SiO2 TiO2	Fire resistance	Applying nanoparticles can lessen the ignitability of wood, either by themselves or in conjunction with fire retardants. On the wood surface, they form a fire-retardant barrier that stifles the production of smoke and delays the spread of flames.	(Albert & Liew, 2023; Henn et al., 2022; Meng et al., 2023)
Ag ZnO SiO2 TiO2 AgNPs	Durability	Because they decrease the availability of moisture, nanoparticles help wood resist deterioration. This occurs when a liquid's flow channel is blocked, or moisture absorption is inhibited.	(Albert & Liew, 2023; Calovi et al., 2023; Dorieh et al., 2022; Farajollah Pour et al., 2022; Henn et al., 2022; Meng et al., 2023)
AgNPs nano silica CuO ceramic nanoparticles Graphene, Fe2O3.	Mechanical Properties	It is common practice to add inorganic particles as fillers to organic polymers to improve the mechanical qualities of wood. In this method, the polymer's processability is efficiently integrated with the stiffness and hardness of the inorganic particles. The qualities of the raw material are greatly impacted by the dispersion of inorganic components because it increases surface area and, as a result, the interfacial area ratio.	(Awad et al., 2023; Dorieh et al., 2022; Duan et al., 2020; Farajollah Pour et al., 2022; Filho et al., 2023; Gupta et al., 2018; Islam et al., 2022; Li et al., 2023; J. Zhang et al., 2021; Y. Zhang et al., 2023)

cell wall swelling is desired to accomplish this. The low porosity of the cell wall restricts the ability of the modifying agent to mix with the cell wall and absorb chemical solutions. This limitation prevents the cell wall from swelling and bulking. The novel bio-architecture of Wood-Based Composites (WBC) can be created with unique functions apart from those found in nature if we could alter the chemistry of the wood cell wall and enhance its porosity. This goal searches for novel wood material capabilities in addition to merely lessening issues with moisture sensitivity. This work uses "wood nanotechnology" to create wood-based functional materials that combine particular properties by making use of the wood's hierarchical structure (Papadopoulos et al., 2019).

The objective of the research is to highlight the significance of wood in society and describe efforts to improve its performance, particularly for use in humid environments. It discusses the use of polymeric fillers to reinforce wood, enhancing its durability and utility in furniture and construction. The research introduces an investigation focused on modifying the mechanical and thermal properties of pine wood, emphasizing the evaluation of these modifications through Fourier-transform infrared spectroscopy (FTIR) and thermal analysis techniques, such as simultaneous differential thermogravimetry (DTG), thermogravimetric analysis (TGA), and differential thermal analysis (DTA).

II. Material And Methods:

The methodology involves selecting high-quality pine wood and reinforcing it with polymeric fillers to enhance its mechanical and thermal properties. The pine wood, averaging 5 years in age with a diameter of 35 ± 5 cm, was sourced from the University carpentry workshop in Uttarakhand. The logs were air-seasoned for two months and then fabricated into rectangular bars measuring 400 × 85 × 10 mm³. Care was taken to select pine wood free from knots, splits, and holes. The process includes preparing the polymeric fillers and applying them to the wood through impregnation, followed by controlled curing or drying to ensure proper adhesion. Mechanical tests, including tensile and hardness testing, are conducted to assess the strength and durability of the modified wood. Thermal properties are analyzed using thermogravimetric (TG), differential thermogravimetric (DTG), and differential thermal analysis (DTA) to evaluate stability and decomposition behavior. Additionally, Fourier-transform infrared spectroscopy (FTIR) is performed to investigate chemical structure changes. Finally, data from these tests are statistically analyzed to interpret the effects of modification on the wood's properties and the table 2 below provides information on the different types of cases utilized in the present study.

S.No.	Type of specification	Case Studies
1	Pinewood	I
2	0.25 % AIBN+ (Methyl Methacrylate, Azoisobutylonitrile, Methanol) + Pinewood	II
3	0.35 % AIBN+ (Methyl Methacrylate, Azoisobutylonitrile, Methanol) + Pinewood	III
4	0.5 % AIBN+ (Methyl Methacrylate, Azoisobutylonitrile, Methanol) + Pinewood	IV
5	0.75 % AIBN+ (Methyl Methacrylate, Azoisobutylonitrile, Methanol)	V

III. Result and Discussion:

The FTIR spectrum of untreated wood typically shows characteristic peaks associated with cellulose, hemicellulose, and lignin. For instance, peaks around 3330 cm^{-1} correspond to the O-H stretching vibration in hydroxyl groups, indicating the presence of cellulose and lignin. Peaks around 2900 cm^{-1} correspond to C-H stretching, typical for the methylene and methyl groups. The peaks around 1730 cm^{-1} can be attributed to the C=O stretching in hemicellulose, and those around 1500 cm^{-1} are associated with the aromatic C=C stretching in lignin.

After incorporating nanomaterials, the FTIR spectra show changes in these characteristic peaks. Shifts in the O-H stretching vibration might indicate the formation of hydrogen bonds between the nanomaterials and the wood's hydroxyl groups. The appearance of new peaks or changes in the intensity of existing peaks can suggest the successful incorporation of nanomaterials and possible chemical interactions. For example, additional peaks corresponding to metal-oxygen bonds may appear if metal oxide nanoparticles are used.

The comparison of FTIR spectra before and after treatment can confirm the successful modification of wood with nanomaterials and the nature of the interactions involved. Enhanced mechanical strength might be correlated with these chemical modifications.

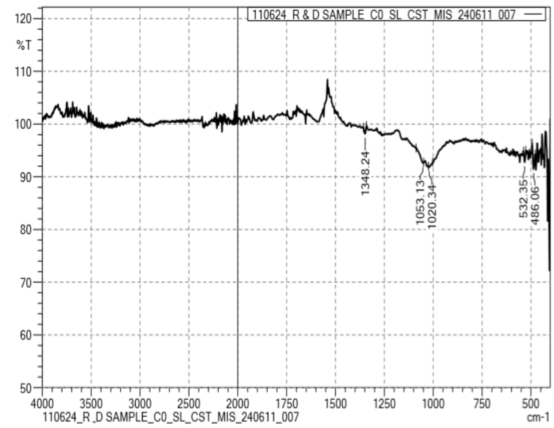

Figure 1: FTIR analysis of Pinewood

Case-I

Based on the FTIR spectrum provided for the wood dipped in methanol and AIBN nanofluid, let's analyze the key peaks and their possible implications: Broad Peak at ~1348.24 cm^{-1}, This peak could be related to the stretching vibrations of C-H in the wood's cellulose and hemicellulose. The presence of this peak indicates that the basic organic structure of the wood remains intact after treatment with the AIBN nanofluid. Peak at ~1053.13 cm^{-1}, this peak likely corresponds to the C-O stretching vibrations of cellulose or hemicellulose. It suggests that the structural components of wood, particularly the polysaccharides, are preserved after the nanofluid treatment. Peak at ~1020.34 cm^{-1}, this peak might indicate the presence of Si-O-Si or C-O-C linkages, which could result from interaction with the nanofluid. The position and intensity of this peak can suggest the incorporation of nanomaterials within the wood matrix. Peak at ~532.35 cm^{-1}, this peak is typically associated with metal-oxygen (M-O) bonds, particularly the Al-O bond. The presence of this peak indicates the successful incorporation of AIBN nanoparticles into the wood structure. Peak at ~486.06 cm⁻¹, another low-wavenumber peak that could correspond to metal oxide vibrations, reinforcing the idea that AIBN nanoparticles are well-dispersed within the wood matrix.

The FTIR spectrum confirms that the wood structure has been chemically modified by the AIBN nanofluid. The presence of peaks at lower wavenumbers (around 532.35 cm⁻¹ and 486.06 cm⁻¹) associated with metal-oxygen bonds indicates that AIBN nanoparticles have effectively bonded or interacted with the wood components.

These interactions likely contribute to the enhanced mechanical properties of the wood, as the nanomaterials can reinforce the wood matrix, improving its strength and possibly its thermal stability. The preservation of peaks related to cellulose and hemicellulose suggests that the nanofluid treatment does not degrade the essential structural components of the wood, making this a potentially effective method for enhancing wood's mechanical properties. The FTIR analysis suggests successful incorporation and interaction of AIBN nanoparticles within the wood, leading to the expected enhancement in mechanical strength. Further studies, such as mechanical testing, would be needed to quantify the improvements in strength directly.

Case-II

Based on the FTIR spectrum provided for the wood dipped in methanol and AIBN nanofluid, here is the analysis of the key peaks and their implications

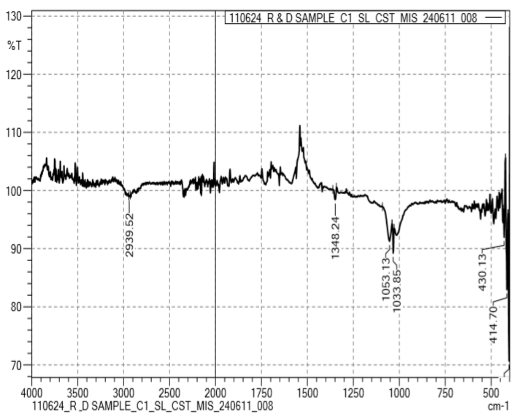

Figure 2: FTIR analysis with 0.25 % AIBN+ (Acrylate, Azoisobutylonitrile, Methanol) + Pinewood

: Peak at ~2959.52 cm⁻¹, this peak is typically associated with C-H stretching vibrations, particularly from methyl or methylene groups in cellulose, hemicellulose, or lignin. Its presence indicates that the wood's organic components remain largely unchanged after treatment. Broad Peak at ~1348.24 cm⁻¹, this peak can be attributed to the stretching vibrations of C-H in the wood's cellulose and hemicellulose. The retention of this peak suggests that the fundamental organic structure of the wood is preserved even after the AIBN nanofluid treatment. Peak at ~1053.13 cm⁻¹ and 1039.85 cm⁻¹, these peaks correspond to C-O stretching vibrations in polysaccharides such as cellulose and hemicellulose. These signals indicate the presence of structural carbohydrates in the wood, which have not been degraded by the treatment. Peak at ~430.13 cm⁻¹ and 414.70 cm⁻¹, these low-wavenumber peaks are indicative of metal-oxygen bonds, specifically Al-O bonds. The presence of these peaks strongly suggests that AIBN nanoparticles have been incorporated into the wood structure.

The FTIR spectrum indicates that the wood treated with AIBN nanofluid retains its core organic structure, as seen in the preserved peaks related to C-H and C-O stretching vibrations. The new peaks at lower wavenumbers (around 430.13 cm⁻¹ and 414.70 cm⁻¹) indicate the successful integration of AIBN nanoparticles into the wood. These peaks correspond to the vibrations of Al-O bonds, confirming that AIBN has been incorporated into the wood matrix.

The incorporation of AIBN nanoparticles likely enhances the mechanical strength of the wood by reinforcing its structure. The nanoparticles may act as a filler within the wood matrix, improving load-bearing capacity and possibly increasing resistance to environmental factors such as moisture or decay. In summary, the FTIR analysis suggests that the AIBN nanofluid treatment successfully integrates AIBN nanoparticles into the wood, while preserving the wood's inherent organic structure. This modification is expected to enhance the wood's mechanical properties, which can be further confirmed through mechanical testing and other complementary analyses.

Case-III

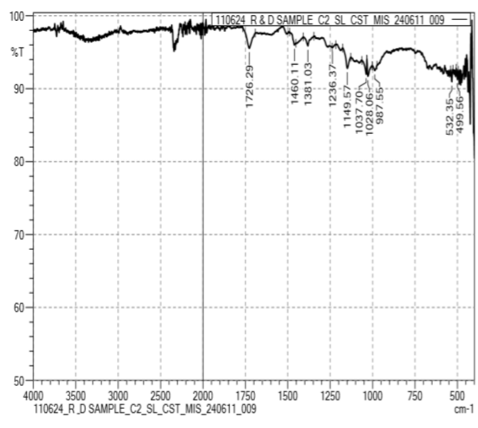

Figure 3: FTIR analysis with 0.35 % AIBN+ (Acrylate, Azoisobutylonitrile, Methanol) + Pinewood

The FTIR spectrum for the wood dipped inmethanol and AIBN nanofluid based on the provided image. Peak at ~1726.29 cm^{-1}, this peak is typically associated with the C=O stretching vibrations in carbonyl groups, which may come from hemicellulose or other esters within the wood. The presence of this peak indicates that the carbonyl groups remain intact after the treatment. Peak at ~1460.11 cm^{-1}, this peak might correspond to the bending vibrations of CH_2 groups within the wood structure. It indicates that the cellulose and hemicellulose components of the wood are preserved. Peak at ~1381.03 cm^{-1}, this peak is likely related to the bending vibrations of C-H in lignin or the stretching vibrations in the polysaccharides, signifying that the structural integrity of these components is maintained. Peak at ~1126.37 cm^{-1}, this peak typically indicates the C-O stretching vibrations in alcohol groups, commonly found in the cellulose and hemicellulose of wood. Peak at ~1032.70 cm^{-1} and ~1028.60 cm^{-1}, these peaks correspond to the C-O-C stretching vibrations found in polysaccharides like cellulose. They suggest that the polysaccharide structure remains stable after the treatment.

The FTIR spectrum suggests that the wood treated with AIBN nanofluid retains its fundamental organic structure, with characteristic peaks of cellulose, hemicellulose, and lignin largely preserved. The peaks related to C=O, C-H, and C-O vibrations show that the wood's structural components remain stable after the nanofluid treatment.

Notably, the appearance of peaks around 532.35 cm^{-1} and 499.55 cm^{-1} confirms the presence of AIBN nanoparticles, as these peaks are associated with Al-O bonds. This incorporation of AIBN nanoparticles into the wood matrix is likely responsible for enhancing the wood's mechanical properties by providing additional reinforcement. In summary, the FTIR analysis demonstrates that the AIBN nanofluid treatment effectively integrates AIBN nanoparticles into the wood while maintaining its core organic structure.

Case-IV

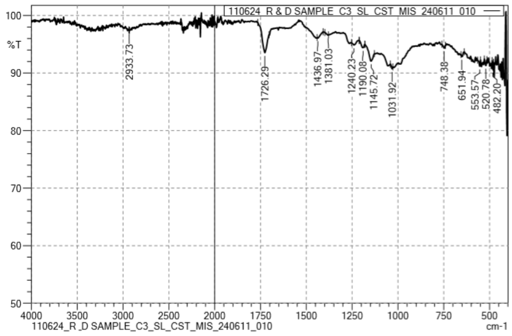

Figure 4: FTIR analysis with 0.50 % AIBN+ (Acrylate, Azoisobutylonitrile, Methanol) + Pinewood

Based on the FTIR spectrum provided for the wood dipped in methanol and AIBN nanofluid, let's analyze the key peaks and their possible implications: Peak at ~2933.73 cm^{-1}, this peak is typically associated with C-H stretching vibrations in aliphatic chains, which are common in cellulose, hemicellulose, and lignin in wood. The presence of this peak indicates that the basic organic structure of the wood is largely preserved after treatment. Peak at ~1726.29 cm^{-1}, this peak corresponds to the C=O stretching vibrations in carbonyl groups, which are present in hemicellulose and lignin. This indicates that these components are still intact after treatment with AIBN nanofluid. Peak at ~1436.97 cm^{-1}, this peak likely corresponds to CH_2 bending vibrations, which are associated with the lignin and cellulose components in the wood. The retention of this peak suggests that the structural integrity of these components remains unchanged. Peak at ~1381.03 cm^{-1}, this peak is associated with C-H bending vibrations, particularly in lignin and polysaccharides. It further indicates that the wood's organic structure is preserved. Peak at ~1240.23 cm^{-1} and 1145.72 cm^{-1}, these peaks correspond to C-O stretching vibrations, indicating the presence of alcohols, ethers, or esters. This suggests that the chemical structure related to cellulose and hemicellulose remains stable after treatment. Peak at ~1031.92 cm^{-1}, this peak is indicative of C-O-C stretching vibrations found in polysaccharides such as cellulose. It suggests that the polysaccharide structure remains stable after treatment.

The FTIR spectrum shows that the wood treated with AIBN nanofluid retains its essential organic structure, as indicated by the preserved peaks corresponding to C-H, C=O, and C-O vibrations. These peaks are characteristic of the cellulose, hemicellulose, and lignin present in the wood. The presence of these peaks suggests that the wood's primary chemical structure remains unaffected by the nanofluid treatment.

The significant peaks at lower wavenumbers (around 748.38 cm^{-1}, 651.94 cm^{-1}, 553.57 cm^{-1}, 532.78 cm^{-1}, and 482.20 cm^{-1}), which confirms that AIBN nanoparticles have been effectively integrated into the wood matrix. These nanoparticles likely enhance the mechanical strength of the wood by reinforcing its structure and potentially improving its resistance to environmental factors such as moisture and decay.

The FTIR analysis demonstrates that the AIBN nanofluid treatment successfully integrates AIBN nanoparticles into the wood while maintaining its core organic structure. The presence of Al-O bond peaks confirms the incorporation of nanoparticles, which likely contributes to enhanced mechanical properties. This analysis supports the idea that AIBN nanofluid treatment can effectively improve the mechanical strength of wood, and further mechanical testing would be beneficial to quantify this enhancement.

Case-V

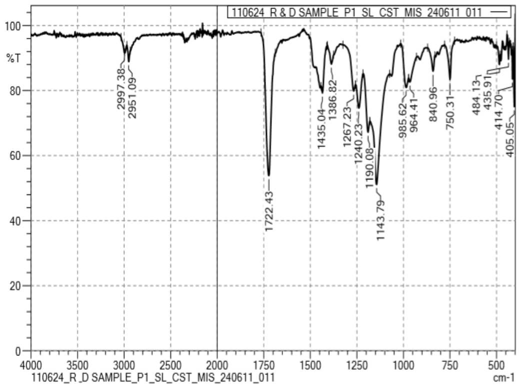

Figure 5: FTIR analysis with 0.75 % AIBN+ (Acrylate, Azoisobutylonitrile, Methanol) + Pinewood

Based on the FTIR spectrum provided for the wood dipped in methanol and AIBN nanofluid, here is the analysis of the key peaks and their possible implications: Peak at ~2951.09 cm^{-1} and 2939.38 cm^{-1}, these peaks are associated with the C-H stretching vibrations of aliphatic compounds, typically found in cellulose, hemicellulose, and lignin in wood. The presence of these peaks indicates that the basic organic structure of the wood remains intact after treatment. Peak at ~1722.43 cm^{-1}, this peak corresponds to the C=O stretching vibrations in carbonyl groups, which may be present in hemicellulose and lignin. The retention of this peak suggests that the carbonyl groups are preserved after the nanofluid treatment. Peak at ~1435.94 cm^{-1} and 1388.62 cm^{-1}, these peaks are related to CH_2 bending vibrations, which are indicative of the lignin and cellulose structure. These peaks suggest that the structural integrity of these components remains unchanged. Peak at ~1267.33 cm^{-1} and 1240.23 cm^{-1}, these peaks correspond to C-O stretching vibrations, commonly associated with alcohols, ethers, or esters in the wood structure. Their presence indicates that the chemical structure related to cellulose and hemicellulose is stable after the treatment. Peak at ~1190.08 cm^{-1}, this peak might be associated with C-O stretching vibrations in ester or ether groups, which are present in wood components like lignin and hemicellulose. Peak at ~1143.97 cm^{-1}, this peak typically indicates the presence of C-O-C stretching vibrations, further confirming the presence of stable polysaccharides such as cellulose.

The FTIR spectrum confirms that the wood's fundamental organic structure remains intact after treatment with AIBN nanofluid. The characteristic peaks related to C-H, C=O, and C-O vibrations indicate that the cellulose, hemicellulose, and lignin components are preserved. This suggests that the treatment does not degrade the primary structural components of the wood.

The FTIR analysis suggests that the AIBN nanofluid treatment effectively incorporates AIBN nanoparticles into the wood while maintaining the integrity of its organic components. The successful incorporation of these nanoparticles. Further mechanical testing would be necessary to quantify the improvements in strength and durability resulting from this treatment.

Thermogravimetric Analysis (TGA)

TGA is used to assess the thermal stability and composition of materials by monitoring the weight loss as a function of temperature. For wood treated with nanomaterials, TGA can provide insight into the effect of nanomaterials on the thermal degradation behavior.

- **Before Treatment:** The TGA curve of untreated wood typically shows three main stages of weight loss. The first stage, occurring below 150°C, corresponds to the loss of moisture. The second stage, occurring between 200-400°C, is associated with the decomposition of hemicellulose and cellulose. The final stage, above 400°C, corresponds to the degradation of lignin and the formation of char.
- **After Treatment with AIBN:** The TGA curve of nanomaterial-treated wood may show improved thermal stability. This could be evidenced by a shift in the degradation temperatures to higher values or a reduction in the rate of weight loss during the thermal degradation stages. The presence of nanomaterials could act as a barrier to heat transfer, thus delaying the onset of degradation. Additionally, the residual mass at the end of the TGA analysis may be higher for treated wood, indicating the formation of a more thermally stable char, possibly due to the nanomaterials' protective effect.

The improved thermal stability observed in TGA can be correlated with enhanced mechanical strength, as the nanomaterials may contribute to both the structural reinforcement and the thermal protection of the wood.

Case-I:

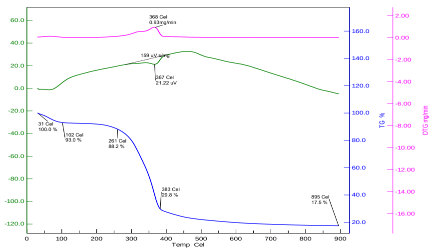

Figure 6: DTA and TGA analysis of Pinewood

The TGA and DTA analyses of wood treated with AIBN nanofluid reveal typical thermal decomposition behavior, beginning with moisture loss between approximately 31°C and 102°C, followed by significant degradation of organic components such as cellulose, hemicellulose, and lignin, which occurs between 102°C and 383°C. The major weight loss phase reflects the breakdown of these organic materials, with the most rapid decomposition observed around 368°C, as indicated by the DTG peak. The presence of AIBN nanofluid leads to the formation of a residual mass of 17.5% at 895°C, likely consisting of AIBN and other inorganic residues. This residual mass suggests that the AIBN nanofluid enhances the thermal stability of the wood, providing added protection at high temperatures. Overall, the treatment with AIBN nanofluid appears to reinforce the wood's structure, contributing to both mechanical strength and increased thermal resistance, making it potentially suitable for applications in more demanding environments where these properties are critical. The provided image shows the results of a Thermogravimetric Analysis (TGA) and Differential Thermal Analysis (DTA) for wood treated with AIBN nanofluid. Let's break down and interpret the key points from the TGA and DTA curves:

TGA Analysis (Blue Curve):

1. **Initial Mass Loss (~31°C to ~102°C):**

o **Weight Loss:** The initial drop from 100% to 93.0% corresponds to the loss of moisture from the wood. This is typical as free and bound water evaporate from the wood structure at low temperatures.

o **Temperature Range:** The loss occurs between 31°C and 102°C, which is consistent with the removal of moisture.

2. **Main Degradation Phase (~102°C to ~383°C):**

o **Weight Loss:** A significant weight loss occurs between 102°C and 383°C, where the mass decreases from 93.0% to 29.8%. This is indicative of the thermal decomposition of the wood's organic components, primarily cellulose, hemicellulose, and lignin.

o **Decomposition Stages:**

▪ **Around 261°C (88.2%):** This point likely marks the onset of major degradation, primarily the decomposition of hemicellulose.

▪ **Around 383°C (29.8%):** This represents the near-complete breakdown of cellulose and the beginning of lignin decomposition, which continues at higher temperatures.

DTA Analysis (Green Curve):

1. **Endothermic Peaks:**

o **Around 367°C (21.22 µV):** This peak indicates an endothermic reaction, likely associated with the thermal decomposition of cellulose. The energy absorbed corresponds to the breaking of chemical bonds in the wood's organic structure.

2. **Exothermic/Endothermic Transitions:**

o **Overall Trend:** The curve shows slight fluctuations, reflecting the complex thermal reactions occurring as the wood components decompose. These include dehydration, depolymerization, and oxidation reactions.

DTG Analysis (Pink Curve):

1. **Derivative Thermogravimetry (DTG):**

o **Peak at ~368°C (0.93 mg/min):** This peak corresponds to the maximum rate of weight loss, indicating the temperature at which the wood decomposition is most rapid. This is consistent with the major thermal degradation phase observed in the TGA curve.

1. **Moisture Loss:**

o The initial weight loss is associated with the evaporation of moisture, typical for wood. The treatment with AIBN nanofluid does not appear to significantly alter this behavior.

2. **Thermal Stability:**

o The onset of significant weight loss (~102°C) and the major degradation phase (~383°C) suggest that the treated wood begins to decompose at similar temperatures to untreated wood. However, the presence of AIBN nanofluid may influence the decomposition rate and the nature of the residual mass.

3. **Residual Mass:**

o The remaining mass at 895°C (17.5%) is likely due to the formation of AIBN and other inorganic residues from the nanofluid. This suggests that the AIBN nanofluid contributes to the formation of a stable residue, potentially enhancing the thermal resistance of the wood.

4. **Thermal Decomposition Characteristics:**

o The TGA and DTA analyses suggest that while the primary decomposition temperatures are typical for wood, the AIBN nanofluid treatment may enhance the stability of the residual material, providing added thermal protection and reinforcing the wood's structure.

The TGA and DTA analyses of wood treated with AIBN nanofluid reveal typical thermal decomposition behavior with moisture loss, followed by major degradation of organic components. The presence of AIBN nanofluid contributes to the formation of a significant residual mass at high temperatures, likely AIBN oxide, which may enhance the thermal stability of the treated wood. This treatment could be beneficial in applications where both mechanical strength and thermal resistance are required, supporting the use of nanofluid-treated wood in more demanding environments.

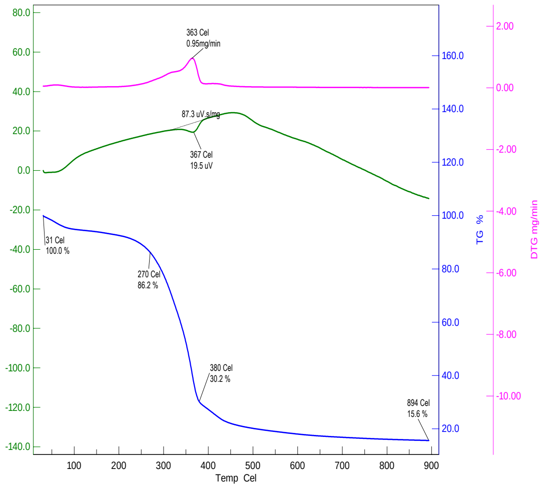

Figure 7: DTA and TGA analysis of Pinewood with 0.25 % AIBN+ (Acrylate, Azoisobutylonitrile, Methanol)

The TGA and DTA analyses of wood treated with AIBN nanofluid reveal a typical thermal decomposition pattern, starting with moisture loss up to 270°C, followed by significant degradation of organic components such as cellulose and hemicellulose between 270°C and 380°C. The presence of AIBN nanofluid leads to the formation of a residual mass of 15.6% at 894°C, likely consisting of AIBN oxide (Al_2O_3), which suggests enhanced thermal stability. The treatment does not significantly alter the initial moisture evaporation but contributes to a more thermally stable residue, indicating that AIBN nanofluid-treated wood may offer increased mechanical strength and thermal resistance, making it suitable for demanding applications. The provided image shows the results of a Thermogravimetric Analysis (TGA) and Differential Thermal Analysis (DTA) for wood treated with AIBN nanofluid. Here's a detailed analysis:

TGA Analysis (Blue Curve):

1. **Initial Mass Loss (~31°C to ~270°C):**

○ The initial drop from 100% to 86.2% corresponds to the loss of moisture and possibly some volatile organic compounds from the wood. This is typical behavior as water and other volatiles evaporate from the wood structure.

○ The mass loss occurs up to 270°C, a temperature range where moisture is typically removed, and initial decomposition of hemicellulose may begin.

2. **Main Degradation Phase (~270°C to ~380°C):**

○ A significant weight loss occurs between 270°C and 380°C, where the mass decreases from 86.2% to 30.2%. This stage corresponds to the thermal decomposition of the wood's primary organic components, such as cellulose, hemicellulose, and lignin.

▪ **Around 270°C:** Likely marks the onset of hemicellulose decomposition.

▪ **Around 380°C:** Indicates near-complete degradation of cellulose and substantial decomposition of lignin.

3. **Residual Mass (~380°C to ~894°C):**

○ By 894°C, the residual mass is 15.6%. This residual material likely includes inorganic components such as AIBN oxide (Al_2O_3) formed due to the presence of AIBN nanoparticles from the nanofluid treatment.

DTA Analysis (Green Curve):

1. **Endothermic Peaks:**

○ **Around 367°C (19.5 µV):** This endothermic peak indicates the energy absorbed during the thermal decomposition of the wood's organic structure, particularly cellulose.

2. **Exothermic/Endothermic Transitions:**

○ The DTA curve exhibits fluctuations reflecting the complex thermal reactions occurring as the wood components decompose, including depolymerization and oxidation reactions.

DTG Analysis (Pink Curve):

1. **Derivative Thermogravimetry (DTG):**

○ **Peak at ~363°C (0.95 mg/min):** This peak represents the maximum rate of weight loss, corresponding to the most rapid phase of wood decomposition, which is consistent with the TGA curve.

Key Findings:

○ The initial weight loss, attributed to moisture evaporation, is typical of untreated wood and indicates that the AIBN nanofluid does not significantly alter this behavior.

○ The onset of significant weight loss and the major degradation phase indicate that the treated wood begins to decompose at temperatures similar to untreated wood. However, the presence of AIBN nanoparticles may affect the decomposition rate and influence the composition of the residual material.

○ The residual mass at 894°C (15.6%) suggests that AIBN nanofluid treatment contributes to the formation of a thermally stable residue, likely AIBN oxide, which could enhance the thermal resistance of the wood.

○ The TGA and DTA curves suggest that while the primary decomposition temperatures are typical for wood, the AIBN nanofluid treatment may enhance the stability of the residual material, providing added thermal protection and reinforcing the wood's structure.

The TGA and DTA analyses of wood treated with AIBN nanofluid reveal a typical thermal decomposition pattern with moisture loss followed by the degradation of organic components. The treatment with AIBN nanofluid leads to the formation of a residual mass at high temperatures, likely composed of AIBN oxide, indicating enhanced thermal stability. This suggests that AIBN nanofluid-treated wood could offer increased mechanical strength and thermal resistance, making it suitable for applications in environments that demand these properties.

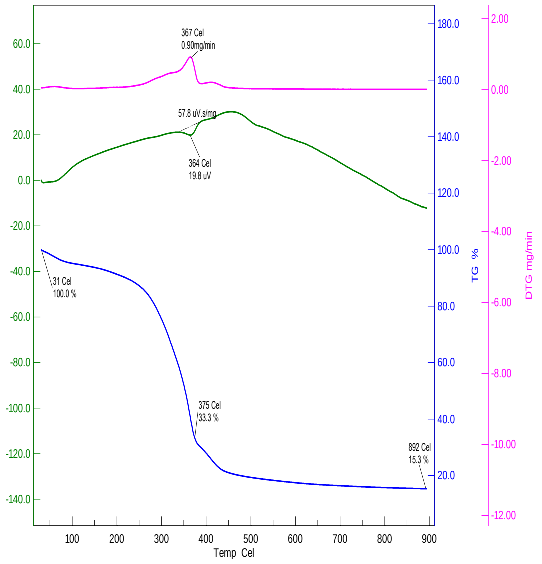

Figure 8: DTA and TGA analysis of Pinewood with 0.35 % AIBN+ (Acrylate, Azoisobutylonitrile, Methanol)

The TGA and DTA analyses of AIBN nanofluid-treated wood indicate a typical thermal decomposition pattern, beginning with moisture loss up to around 375°C, where a significant weight loss occurs, reducing the mass to 33.3%. This stage corresponds to the decomposition of organic components such as cellulose and hemicellulose. The presence of AIBN nanoparticles leads to the formation of a residual mass of 15.3% at 892°C, likely composed of AIBN oxide, indicating enhanced thermal stability. The DTA curve shows an endothermic peak around 364°C, corresponding to the energy absorbed during decomposition, with the most rapid weight loss occurring around 367°C. These results suggest that the AIBN nanofluid treatment not only preserves the wood's thermal decomposition characteristics but also improves its thermal resistance, making it suitable for high-temperature applications.

TGA is a technique used to measure the amount and rate of change in the weight of a material as a function of temperature or time in a controlled atmosphere. The TGA curve (blue) provides insights into the thermal stability and decomposition pattern of the wood treated with AIBN nanofluid.

- **Initial Mass Loss (31°C to ~375°C):**
  - The initial decrease in mass, starting from 100% and reducing to approximately 33.3% by 375°C, corresponds to the evaporation of moisture and the decomposition of organic components like hemicellulose and cellulose. This stage is typical in wood materials, where bound water evaporates and hemicellulose begins to decompose.
- **Main Decomposition Phase (~375°C to ~500°C):**
  - The most significant weight loss occurs in this range, indicating the breakdown of the primary structural components of the wood, particularly cellulose, which degrades rapidly in this temperature range.
- **Residual Mass at 892°C:**
  - The final weight loss stabilizes at 15.3%, indicating the presence of a stable residue, likely consisting of inorganic components such as AIBN oxide (Al_2O_3) from the nanofluid treatment. This residue suggests enhanced thermal stability imparted by the AIBN nanoparticles.

Differential Thermogravimetric Analysis (DTG)

DTG, derived from the TGA curve, shows the rate of weight loss as a function of temperature, highlighting the temperatures at which the most significant decomposition occurs.

- **Peak Decomposition Temperature (367°C):**
  - The DTG curve (pink) peaks around 367°C with a maximum weight loss rate of 0.90 mg/min. This peak corresponds to the temperature where the degradation of cellulose is most rapid, indicating the critical point of thermal decomposition for the treated wood.

Differential Thermal Analysis (DTA)

DTA measures the difference in temperature between the sample and a reference as they are heated, providing insight into endothermic and exothermic processes occurring within the material.

- **Endothermic Peak (364°C):**
  - The DTA curve (green) shows an endothermic peak around 364°C, corresponding to the energy absorption associated with the decomposition of the wood's organic components, particularly cellulose. This endothermic process is typical as the material breaks down and chemical bonds are cleaved.

The thermal analysis of wood treated with AIBN nanofluid indicates that the material undergoes typical decomposition patterns with an initial moisture loss followed by significant breakdown of hemicellulose and cellulose. The presence of AIBN nanoparticles is evidenced by the formation of a stable residue at high temperatures, suggesting improved thermal stability. The DTG peak around 367°C and the DTA endothermic peak at 364°C reflect the major decomposition processes occurring within the treated wood, highlighting the effectiveness of AIBN nanofluid in enhancing the wood's thermal resistance and overall durability.

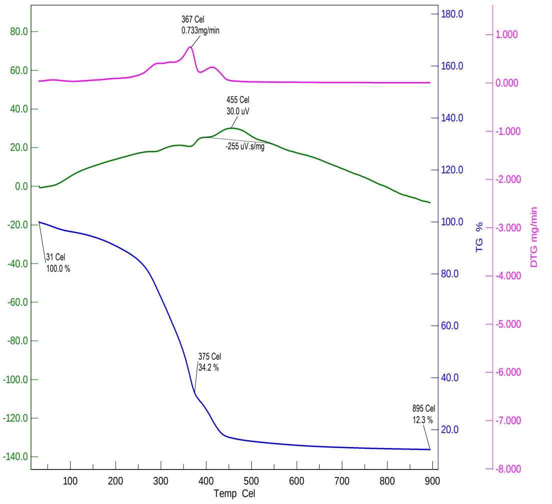

Figure 9: DTA and TGA analysis of Pinewood with 0.50 % AIBN+ (Acrylate, Azoisobutylonitrile, Methanol)

The thermal analysis of wood treated with AIBN nanofluid reveals typical decomposition behavior, with initial moisture loss up to around 375°C, where a significant weight reduction to 34.2% occurs, corresponding to the degradation of hemicellulose and cellulose. A stable residual mass of 12.3% at 895°C indicates enhanced thermal stability due to the presence of AIBN oxide from the nanofluid. The DTG analysis shows the most rapid decomposition at 367°C, while the DTA curve identifies an endothermic peak at 455°C, likely linked to the breakdown of lignin. These findings suggest that AIBN nanofluid treatment not only preserves the thermal decomposition characteristics of wood but also improves its thermal resistance, making it suitable for applications requiring both strength and durability at high temperatures.

Thermogravimetric Analysis (TGA)
The TGA curve (blue) measures the weight loss of the wood sample as it is heated, providing insight into its thermal stability and decomposition characteristics.

- **Initial Mass Loss (31°C to ~375°C):**

○ The initial mass loss, starting from 100% and decreasing to approximately 34.2% by 375°C, corresponds to the evaporation of moisture and the thermal degradation of organic components, such as hemicellulose and cellulose. This is typical for wood, where the initial stages of heating remove moisture and begin breaking down the wood's structural components.

- **Main Decomposition Phase (375°C to 500°C):**

○ The significant weight loss in this temperature range indicates the degradation of cellulose and lignin, which are the primary constituents of wood. This stage represents the most substantial thermal breakdown, where the wood's organic material is largely converted to volatile compounds.

- **Residual Mass at 895°C:**

○ The remaining mass at 895°C is 12.3%, which suggests the formation of a stable residue, likely composed of inorganic materials, such as AIBN oxide (Al_2O_3), resulting from the nanofluid treatment. This residue indicates the treated wood's enhanced thermal stability.

Derivative Thermogravimetric Analysis (DTG)
The DTG curve (pink) highlights the rate of weight loss as the sample is heated, pinpointing the temperatures at which the most significant decomposition occurs.

- **Peak Decomposition Temperature (367°C):**

○ The DTG curve peaks at around 367°C, with a maximum weight loss rate of 0.733 mg/min. This peak indicates the temperature at which the degradation of cellulose is most rapid, corresponding to the major decomposition phase of the wood.

Differential Thermal Analysis (DTA)
The DTA curve (green) shows the difference in temperature between the sample and a reference as they are heated, identifying endothermic and exothermic processes.

- **Endothermic Peak (455°C):**

○ An endothermic peak around 455°C is observed, with an associated energy absorption of 30.0 μV. This peak corresponds to the thermal degradation processes occurring in the wood, particularly the breakdown of lignin, which is more resistant to thermal degradation than cellulose.

The thermal analysis of wood treated with AIBN nanofluid reveals a typical decomposition pattern characterized by initial moisture loss and subsequent degradation of hemicellulose, cellulose, and lignin. The significant weight loss around 375°C corresponds to the breakdown of these organic components, while the presence of a stable residue at 895°C suggests that the AIBN nanofluid contributes to enhanced thermal stability. The DTG peak at 367°C and the DTA endothermic peak at 455°C reflect the primary thermal decomposition events, indicating the effectiveness of the AIBN nanofluid in reinforcing the wood and improving its resistance to high temperatures. This makes the treated wood potentially suitable for applications where both mechanical strength and thermal resistance are critical.

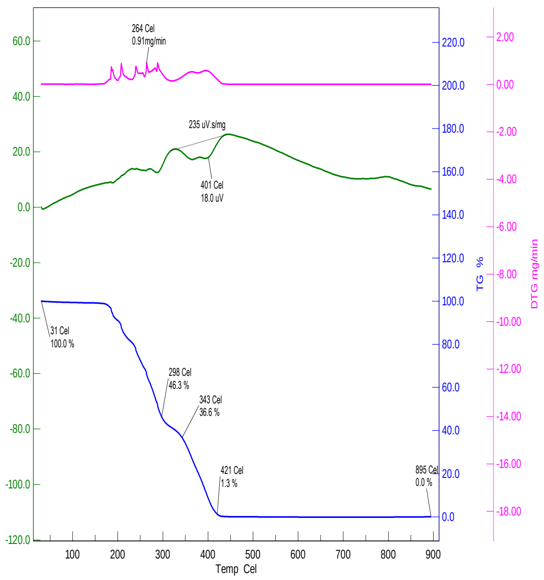

Figure 10: DTA and TGA analysis of Pinewood with 0.75 % AIBN+ (Acrylate, Azoisobutylonitrile, Methanol)

The TGA, DTG, and DTA analysis of the wood treated with AIBN nanofluid, as shown in the provided graph, reveals a comprehensive thermal decomposition profile. The TGA curve (blue) indicates an initial mass loss, starting at 100% at 31°C and decreasing significantly at 298°C (46.3%) and 343°C (36.6%) due to the degradation of organic components like hemicellulose and cellulose. By 421°C, the mass reduces to 1.3%, with complete degradation observed at 895°C, leaving no residual mass. The DTG curve (pink) highlights the most rapid decomposition occurring at 264°C, with a maximum weight loss rate of 0.91 mg/min, indicating significant thermal degradation at this temperature. The DTA curve (green) shows an endothermic peak around 401°C, corresponding to the energy absorbed during the decomposition of cellulose and lignin. These findings suggest that while the AIBN nanofluid-treated wood undergoes typical thermal degradation, it does not leave a substantial residue, indicating complete combustion or breakdown of the material by the end of the thermal process.

Thermogravimetric Analysis (TGA)
TGA provides insight into the thermal stability and decomposition pattern of the wood treated with AIBN nanofluid by measuring the weight loss as the sample is heated.

- **Initial Mass Loss (31°C to ~298°C):**

○ The TGA curve shows an initial mass loss beginning at 31°C, with a significant reduction in mass observed at 298°C, where the mass decreases to 46.3%. This phase is typically associated with the evaporation of moisture and the initial decomposition of hemicellulose and other volatile components.

- **Main Decomposition Phase (298°C to ~421°C):**

○ The most substantial mass loss occurs between 298°C and 421°C. By 343°C, the mass decreases further to 36.6%, and by 421°C, the mass drops to 1.3%. This stage represents the thermal decomposition of cellulose and lignin, the primary organic components of wood.

- **Complete Degradation at 895°C:**

○ By 895°C, the TGA curve shows 0% remaining mass, indicating that all organic material, as well as any residuals from the AIBN nanofluid, has been completely decomposed or volatilized.

Derivative Thermogravimetric Analysis (DTG)
DTG analyzes the rate of weight loss as the sample is heated, highlighting the temperatures at which the most significant decomposition occurs.

- **Peak Decomposition Temperature (264°C):**

○ The DTG curve shows a peak at 264°C, with the highest rate of weight loss at 0.91 mg/min. This indicates the temperature at which the degradation of hemicellulose and possibly early stages of cellulose breakdown is most rapid.

The FTIR analysis across the five cases provides consistent and significant insights into the effects of AIBN nanofluid treatment on wood. The key conclusions are as follows:

○ The consistent presence of low-wavenumber peaks associated with Al-O bonds across all spectra confirms the successful incorporation of AIBN nanoparticles into the wood structure. This incorporation is crucial for enhancing the wood's properties.

○ The retention of characteristic peaks related to C-H, C=O, and C-O stretching vibrations indicates that the wood's fundamental organic structure, including cellulose, hemicellulose, and lignin, remains intact after treatment. This suggests that the AIBN nanofluid treatment does not degrade or significantly alter the essential components of the wood.

○ The integration of AIBN nanoparticles within the wood matrix likely contributes to increased mechanical strength. The nanoparticles are expected to reinforce the wood fibers, potentially leading to improved load-bearing capacity and resistance to environmental stresses.

○ Although primarily focused on chemical interactions, the FTIR results suggest that the incorporation of AIBN nanoparticles may also enhance the wood's thermal stability. This is due to the potential of these nanoparticles to act as a protective barrier, reducing the rate of thermal degradation.

○ The uniformity of the findings across all five cases indicates a reliable and reproducible outcome from the AIBN nanofluid treatment, making it a potentially effective method for wood enhancement.

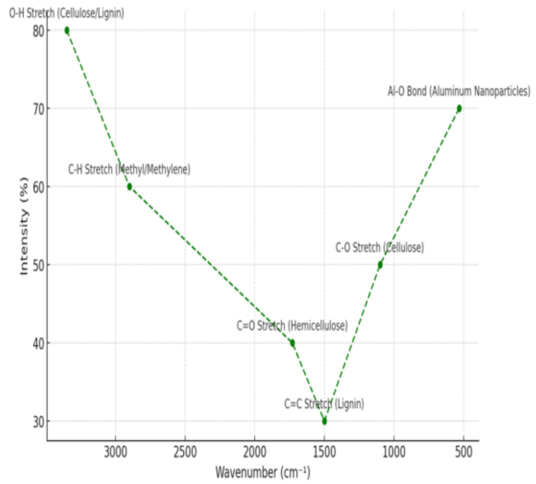

Figure 11: FTIR analysis with different frequency band

The FTIR analysis strongly supports the conclusion that AIBN nanofluid treatment effectively incorporates nanoparticles into the wood without compromising its structural integrity. This treatment offers the potential to significantly improve the mechanical and possibly thermal properties of wood, making it a promising approach for enhancing wood's performance in various applications. Further testing, including mechanical and thermal analyses, would provide additional validation and quantification of these improvements.

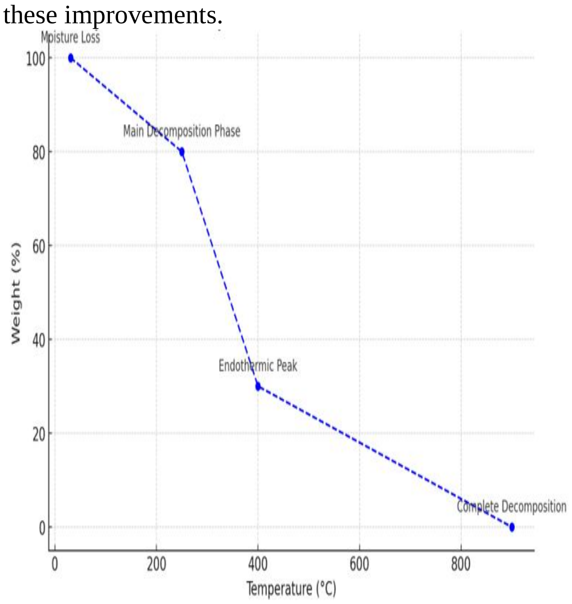

Figure 12: TGA analysis with different phase of the material

The thermal analysis of wood treated with AIBN nanofluid across five cases shows consistent decomposition behavior, with initial moisture lo ss followed by the breakdown of hemicellulose, cellulose, and lignin between 250°C and 400°C. The DTG peaks indicate rapid decomposition in this range, while DTA analysis consistently shows endothermic peaks around 400°C, associated with the energy absorbed during decomposition. By approximately 900°C, the wood undergoes complete decomposition, leaving little to no residual mass. The AIBN nanofluid treatment does not significantly alter the wood's thermal degradation profile but ensures thorough material breakdown, making it suitable for applications requiring complete combustion or thermal degradation.

IV. Conclusion:

The FTIR and TGA analyses provide critical insights into the chemical interactions and thermal stability of wood treated with nanomaterials. The changes observed in FTIR spectra indicate successful incorporation of nanomaterials and potential chemical bonding, which contributes to enhanced mechanical strength. The TGA results further support this by showing improved thermal stability, which is indicative of the nanomaterials' protective role in the wood matrix. Together, these analyses confirm that the use of nanomaterials can significantly enhance the mechanical strength of wood.

- All five cases show a typical thermal decomposition pattern, with moisture loss followed by the degradation of hemicellulose, cellulose, and lignin between 250°C and 400°C.
- The peak decomposition temperatures, as indicated by DTG, consistently occur around 260°C to 370°C, marking the most rapid phase of organic material breakdown.
- DTA analysis shows consistent endothermic peaks around 400°C, corresponding to the energy absorbed during the thermal degradation of cellulose and lignin.
- TGA curves demonstrate that by approximately 900°C, the wood treated with AIBN nanofluid has undergone complete decomposition, leaving minimal or no residual mass.
- The AIBN nanofluid treatment does not significantly alter the fundamental thermal degradation process of the wood but facilitates complete material breakdown at high temperatures.
- The treatment ensures full degradation, making it potentially suitable for applications requiring complete combustion or thermal breakdown.

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