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EVALUATING THERMAL STABILITY AND FIRE RESISTANCE OF NANOFILLER REINFORCED POLYMER COMPOSITES FOR ADVANCED ENGINEERING APPLICATIONS

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ABSTRACT
Polymer composites support lightweight engineering across transport, construction, electronics and energy systems, but thermal degradation and flammability constrain their use in demanding environments. Nanofiller reinforcement offers opportunities to modify heat transfer, decomposition behaviour and protective char formation, although performance depends on filler chemistry, dispersion, loading and interactions with the polymer matrix. This study proposes a comparative evaluation of thermal stability and fire resistance in nanofiller reinforced polymer composites for advanced engineering applications. Unfilled polymers and reinforced formulations are compared using thermogravimetric analysis, differential scanning calorimetry, flammability testing and cone calorimetry. Key indicators include decomposition temperatures, residual char, ignition time, heat release, smoke production and mechanical property retention. Microscopy and chemical characterisation examine dispersion, interfacial behaviour and degradation mechanisms. The analysis considers processing conditions, specimen geometry and testing variability to distinguish reproducible improvements from formulation dependent effects. Particular attention addresses trade-offs involving processability, strength, smoke generation and material cost. The proposed evaluation provides a basis for selecting promising formulations while recognising that laboratory performance requires application specific validation before claims concerning component safety, durability or regulatory compliance are justified under service conditions.

Keywords:
Polymer composites; Nanofillers; Thermal stability; Fire resistance; Flame retardancy; Thermal degradation.

1. INTRODUCTION: FROM LIGHTWEIGHT MATERIALS TO FIRE-SAFE ENGINEERING

1.1 Engineering Opportunities and Thermal Vulnerabilities

Polymer composites support engineering applications in transport, electrical equipment, construction and energy systems, where low mass, adaptable processing and component integration offer practical advantages [1]. Their suitability nevertheless depends on behaviour under both normal operating temperatures and abnormal thermal exposure. Softening can compromise dimensional stability and load-bearing capacity before substantial decomposition occurs. Subsequent degradation can generate combustible products, enabling ignition and sustained burning when sufficient heat and oxygen are available [2]. These processes require separate assessment because thermal stability and fire performance describe different responses. A higher decomposition temperature does not necessarily indicate lower heat release, reduced smoke or improved component safety. Specimen thickness, orientation, ventilation and exposure intensity also influence measured behaviour [3]. Consequently, material evaluation must reflect the intended application rather than rely on one favourable laboratory indicator. A defensible comparison considers decomposition, ignition, combustion and retained function within clearly defined exposure conditions and documented practical engineering requirements.

1.2 Nanofillers as Multifunctional Modifiers

Nanofillers introduce opportunities to modify polymer behaviour through their geometry, surface chemistry and interactions with the surrounding matrix. Representative materials include layered silicates, carbon nanotubes, graphene-derived structures and metal oxides [4]. Their potential contributions include restricting volatile transport, reinforcing protective residues and modifying heat transfer or decomposition pathways. Carbon-based networks, for example, can influence surface-layer integrity during combustion [5]. However, effectiveness depends on filler loading, dispersion, orientation and compatibility, rather than nanoscale dimensions alone [6]. Agglomeration can interrupt barrier formation, while altered conductivity can redistribute heat in ways that do not consistently delay ignition. Certain filler chemistries or surface treatments may accelerate degradation, and changes in combustion can affect smoke production [7]. These competing effects make multifunctional assessment

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necessary across the selected matrix and fillers. Nanofiller reinforcement therefore represents a formulation strategy requiring verification, not an inherently flame-retardant material category.

1.3 Study Purpose and Comparative Questions

This manuscript presents a proposed evaluation protocol comparing thermal and fire responses across controlled nanofiller formulations. The principal question concerns whether improvements remain consistent across decomposition, ignition and combustion assessments. Additional comparisons examine smoke, mechanical retention and processing limitations. An unfilled matrix and a justified benchmark provide reference points, while independent batches support evaluation of reproducibility. The contribution is a transparent assessment linking measured benefits and limitations to application relevance. Consistent with scenario-dependent fire evaluation, no single metric determines suitability [8]. Defining exposure conditions, performance requirements and unacceptable trade-offs therefore precedes formulation selection, ensuring that subsequent laboratory comparisons address a clear engineering decision rather than an assumed improvement in practice.

2. DEFINING THE PERFORMANCE ENVELOPE AND COMPARISON LOGIC

2.1 Application Conditions and Failure Scenarios

The protocol focuses on polymer composite housings for electrical equipment, where thermal exposure can arise from normal operation, internal faults or an external fire. Operating specifications establish permissible temperatures and durations, rather than assigning a universal temperature limit to all matrices. Routine heating is distinguished from abnormal overheating, which can soften the enclosure or initiate decomposition, and from sustained external exposure. Potential ignition sources include hot surfaces, electrical arcing and nearby burning materials. Ventilation, enclosure openings and adjacent combustibles influence the resulting scenario [6]. Specimen thickness and orientation therefore accompany every laboratory comparison. Relevant consequences include distortion, reduced stiffness, flaming droplets and damage to neighbouring equipment. Material specimens support comparisons of decomposition, ignition and heat release, but cannot establish enclosure performance independently [7]. Component assessment additionally considers joints, openings, mounting arrangements and functional requirements. The assessment boundary consequently identifies both the evidence available from specimens and the additional validation required before selecting materials for an equipment configuration and service environment.

2.2 Separate Thermal Stability, Flammability and Fire Resistance

Thermal stability describes resistance to decomposition under stated temperature, atmosphere and exposure conditions. It differs from resistance to softening, which can occur before substantial mass loss. Flammability concerns ignition and combustion behaviour, including sustained burning under specified conditions. Fire resistance concerns maintaining required functions during fire exposure, assessed using an applicable component or assembly procedure rather than a material classification alone [8]. The terminology in this manuscript follows those distinctions. Thermogravimetry 101characterized mass change during a defined heating programme but does not directly measure flame spread or structural function. Oxygen-index testing identifies the oxygen concentration supporting combustion of specified specimens [9]. Small-flame classifications describe behaviour under their ignition and orientation conditions [10]. Neither result independently demonstrates enclosure integrity during a developed fire. Accordingly, improved thermal stability, favourable flammability classification and verified component performance remain separate conclusions requiring appropriate evidence, with limitations stated wherever the selected tests cannot resolve application-specific requirements.

2.3 Hypothesised Mechanisms and Competing Effects

Potential benefits arise when dispersed nanofillers form barriers that restrict volatile escape or modify heat transfer through the degrading material. Layered particles can increase transport-path complexity, while connected carbon structures can reinforce surface residues [11]. Catalytic activity may promote protective char, but it may also accelerate decomposition before a useful barrier develops. Existing stabilisers and flame-retardant additives can interact with filler surfaces, complicating attribution. Increased thermal conductivity can redistribute heat without necessarily reducing combustion or delaying ignition [12]. Processing-related changes, including altered viscosity, dispersion and matrix degradation, must therefore be distinguished from mechanisms operating during burning. Microscopy, thermal analysis, residue characterization and calorimetry provide complementary tests of these propositions. Competing explanations include combustible-content dilution, specimen differences and agglomeration. Mechanisms remain hypotheses until consistent measurements support them; improved residue appearance alone cannot demonstrate an effective protective barrier throughout the exposure scenario.

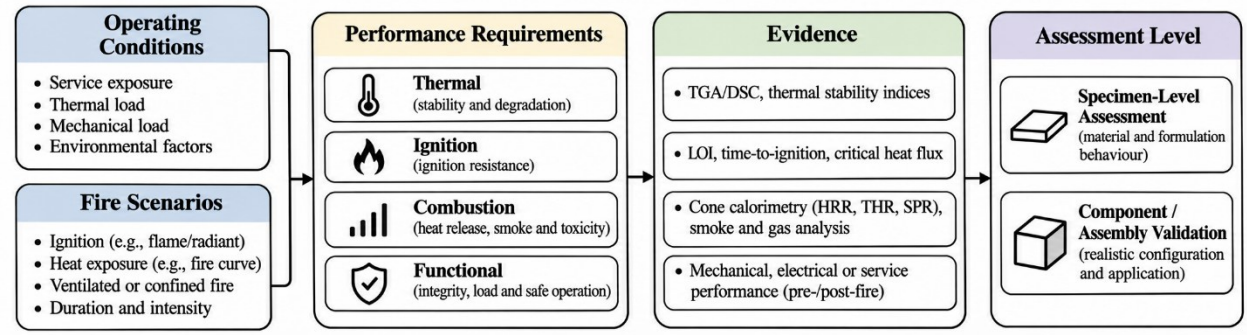
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2.4 Benchmarks and Acceptance Principles

The unfilled matrix provides the primary control, manufactured and conditioned using equivalent procedures. A conventional flame-retardant or documented commercial formulation adds a benchmark where composition and specimen conditions permit meaningful comparison. Test-method standards define measurement procedures, while product classifications and application requirements address different decisions [13]. Primary indicators include ignition behaviour, heat release, smoke and mechanical retention. Unacceptable trade-offs are specified before results, including excessive smoke or impaired processing. No single indicator establishes overall fire safety [14]. This performance envelope guides material selection and matched experimental controls, ensuring that subsequent comparisons isolate nanofiller effects rather than uncontrolled differences between formulations.

Figure 1. Application-to-evidence assessment map.



3. BUILDING A CONTROLLED MATERIAL COMPARISON

3.1 Matrix, Nanofiller and Benchmark Selection

The protocol selects injection-moulding polypropylene as a model matrix for electrical equipment housings, without implying that unmodified polypropylene meets enclosure acceptance requirements. A single documented grade provides the starting material, with supplier, lot number, melt flow specification and stabiliser package recorded before procurement. Additive disclosure matters because existing stabilisers or flame retardants can interact with nanofillers and influence interpretation [12]. Virgin pellets with documented storage and processing history reduce uncertainty associated with unknown prior exposure. The comparison includes layered silicate, multiwalled carbon nanotube and zinc oxide fillers, representing contrasting geometries and surface chemistries [13]. Supplier records specify dimensions, purity, surface treatment and moisture guidance. Microscopy checks representative morphology rather than accepting nominal nanoscale dimensions alone. A conventional flame-retardant polypropylene formulation provides a benchmark only when its composition and preparation are sufficiently documented [14]. Proprietary differences remain explicit limitations. Actual supplier identities and product codes require confirmation before experimental implementation, and retained samples support investigation of discrepancies between documentation and observations.

3.2 Formulation Design and Experimental Controls

Filler content is expressed as percentage of total dry formulation mass, with the polymer and other additives completing the balance. Screening uses matched low, intermediate and high concentrations selected through processability trials, rather than assuming identical feasible ranges for every filler. The unfilled matrix undergoes the same extrusion and moulding history as reinforced groups. Where a dispersant or compatibiliser is necessary, a matrix-plus-additive control separates its contribution from the nanofiller effect [15]. Surface-modified and unmodified variants are compared at matched inorganic or carbon filler content, accounting for any organic coating. Hybrid systems containing conventional flame retardants form a separate comparison, not an extension of nanofiller-only results [12]. A blocked factorial design evaluates filler type and concentration, with modification examined within a justified subset. Three independent compounding batches per formulation provide planned manufacturing replication. Specimen counts follow test requirements and precision objectives. Preparation order is randomised within practical equipment-cleaning blocks. This structure supports interpretable comparisons while avoiding unsupported attribution to a single ingredient when composition or processing differs between experimental groups [14].

3.3 Dispersion, Processing and Specimen Production

A co-rotating twin-screw extruder compounds the thermoplastic formulations before pelletisation and injection moulding. The processing record specifies screw configuration, feeding order, barrel temperatures, screw speed,

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throughput and estimated residence time. Preliminary trials establish a workable temperature and shear window without assigning unverified operating settings. Matrix pellets and fillers receive drying appropriate to their documented moisture sensitivity, followed by sealed storage. Feeding arrangements minimise segregation and support reproducible dispersion. Moulding records include pressure, tool temperature, cooling time and specimen orientation, consistent with polypropylene preparation principles [16]. Thickness and surface finish remain controlled because geometry influences fire-test responses [14]. Microscopy examines agglomerates and spatial distribution, while suitable diffraction measurements support assessment of layered silicate structure. Carbon filler damage and matrix degradation require separate checks where processing severity makes them plausible [13]. Settling is assessed where relevant to the preparation route, and batch inconsistencies remain documented. Enclosed transfer, extraction and suitable cleaning reduce exposure during powder handling [17]. Controls also address hot processing emissions, with protective measures selected through the laboratory risk assessment rather than assuming that embedded nanofillers eliminate all exposure concerns.

3.4 Conditioning, Replication and Traceability

Specimens receive a defined conditioning atmosphere, provisionally 23°C and 50% relative humidity, with tolerances and duration specified before testing. ISO 291 informs atmospheric control, while individual test requirements determine any additional preparation [18]. Allocation reserves material from every manufacturing batch for thermal, fire, mechanical and structural assessments. Identifiers link matrix and filler lots, compounded pellets, moulding runs and individual specimens. Independent batches represent manufacturing replication; repeated specimens from one batch estimate within-batch variation and do not create additional independent batches [19]. Randomised allocation limits systematic differences between assessment streams. Deviations, damaged specimens and exclusion decisions enter the record before comparative analysis. Retained samples and processing logs support subsequent investigation. Balanced specimen availability enables matched comparisons across methods. These controls establish a traceable basis for examining decomposition behaviour before interpreting ignition, combustion and retained mechanical function under the selected exposure conditions.

Table 1. Formulation design and comparison controls.

Formulation/group	Matrix and nanofiller specification	Loading basis	Processing controls	Independent replication	Comparison purpose
Unfilled matrix	Documented polypropylene grade	0% nanofiller	Matched extrusion, moulding and conditioning	Three planned manufacturing batches	Establish matrix response and processing baseline
Matrix-plus-additive control	Same polypropylene with required dispersant or compatibiliser	Additive percentage of total dry formulation mass	Matched additive concentration and processing history	Three planned manufacturing batches	Separate additive effects from nanofiller effects
Layered silicate formulations	Same polypropylene; documented platelet dimensions and surface chemistry	Prespecified concentrations by total dry mass	Controlled drying, feeding, shear and specimen geometry	Three planned batches per concentration	Examine loading-dependent behaviour of layered particles
Carbon nanotube formulations	Same polypropylene; documented nanotube dimensions, purity and treatment	Prespecified concentrations by total dry mass	Controlled dispersion and assessment of processing damage	Three planned batches per concentration	Examine carbon-network effects and associated trade-offs
Zinc oxide formulations	Same polypropylene; documented particle dimensions and surface chemistry	Prespecified concentrations by total dry mass	Controlled feeding, agglomeration assessment and moulding	Three planned batches per concentration	Compare oxide-based modification with other filler classes

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Formulation/group	Matrix and nanofiller specification	Loading basis	Processing controls	Independent replication	Comparison purpose
Surface-modification subset	Matched untreated and surface-modified filler variants	Equivalent filler content, accounting for coating mass	Matched matrix, additive controls and processing	Three planned batches per variant	Isolate surface-modification effects
Conventional benchmark	Documented flame-retardant polypropylene formulation	Fully recorded formulation proportions	Equivalent specimen preparation where feasible	Three planned batches if manufactured within the study	Establish a practical comparator
Optional hybrid subset	Polypropylene, selected nanofiller and conventional flame retardant	Each constituent recorded separately	Matched conventional-additive control and processing	Three planned batches per formulation	Investigate combined effects without conflating comparison groups

4. CONNECTING DECOMPOSITION BEHAVIOUR WITH FIRE RESPONSE

4.1 Thermal Degradation Under Controlled Atmospheres

Thermogravimetric analysis follows ISO 11358-1 principles, comparing matched formulations under nitrogen and air where oxidative behaviour is relevant [20]. The proposed programme uses approximately 10 mg per specimen, heating from 30°C to 800°C at 10°C/min, with a nominal purge flow of 50 mL/min. Instrument compatibility, adequate purging and specimen behaviour determine final settings before testing. Actual masses, crucibles, gas purity and flow rates accompany every result. The primary onset indicator is the temperature at 5% initial mass loss, explicitly distinguished from extrapolated tangent onset. Temperatures at 10% and 50% loss, derivative mass-loss peaks and final residual fractions provide complementary comparisons. Moisture or surface-treatment loss is identified rather than automatically interpreted as matrix decomposition. Residue includes inorganic filler and potentially polymer-derived char; oxidative follow-up and compositional evidence help distinguish them. Carbon fillers require particular care because they can also oxidise. Heating rate, atmosphere and mass influence apparent decomposition through kinetic and transport effects [20]. Accordingly, formulations are compared under identical settings, and dynamic heating results are not interpreted as continuous service-temperature ratings or proof of long-term functional stability under actual operating conditions.

4.2 Thermal Transitions and Heat Transport

Differential scanning calorimetry examines melting and 104ecognizing104ion using heating, cooling and reheating cycles consistent with ISO 11357 principles [21]. The first heating records manufacturing history; cooling and subsequent heating support comparisons under a thermal programme. Temperature limits, rates, atmosphere and calibration materials remain specified before measurement. Enthalpies are reported per total specimen mass and, where interpreted as polymer crystallinity, 104ecognizin to the polymer fraction with the reference enthalpy identified. Filler-related dilution must not masquerade as altered crystallinity. Glass-transition behaviour is assessed only where the method and temperature range resolve it reliably. Where heat transport is central, conductivity or diffusivity measurements document temperature, direction, specimen dimensions and contact conditions. Increased conductivity may redistribute heat without improving decomposition resistance. Transition shifts therefore inform processing compatibility and dimensional behaviour, while thermogravimetry addresses decomposition separately [20]. Interpretation relates both measurements to operating conditions rather than treating a higher transition temperature as proof of fire safety.

4.3 Ignition, Burning Behaviour and Heat Release

The fire assessment combines oxygen-index testing, a selected small-flame procedure and cone calorimetry because each addresses a different question [22]. Oxygen index identifies the minimum oxygen fraction supporting specified burning, whereas small-flame testing describes extinguishment, continued burning and dripping under a defined ignition sequence. Classification includes specimen thickness, orientation and conditioning, preventing transfer of a rating to untested geometries. The protocol records dimensions, exposed area, density and preparation for every formulation. Cone calorimetry uses a prespecified irradiance, provisionally 35 kW/m², with an external spark igniter and documented specimen holder, backing and edge restraint. Final conditions follow the adopted method and application rationale. Ignition time, peak heat-release rate, total heat

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release, mass loss and flaming duration are reported where measurable. Nonignition is recorded against exposure duration rather than assigned an arbitrary ignition time. Observations document dripping, swelling, cracking, extinguishment and residue development. All groups undergo equivalent exposure, and repeat specimens represent independent manufacturing batches where feasible [19]. A favourable small-flame classification can coexist with substantial heat release during sustained irradiation because the ignition source, feedback and duration differ [22]. Consequently, rankings remain method-specific, and calorimetric gains do not independently demonstrate enclosure fire resistance. Deviations, specimen collapse and test termination receive explicit documentation before quantitative comparisons are accepted and retained in study records.

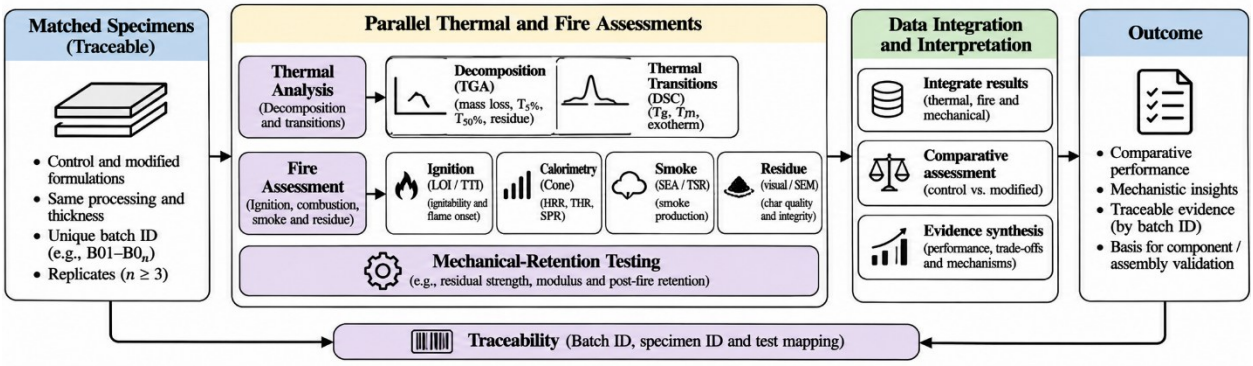
4.4 Smoke, Combustion Products and Protective Residues

Smoke assessment reports only indicators supported by the equipment, including smoke-production rate and total smoke release where available. Optical smoke measurements describe obscuration and do not independently establish toxicity. Instrumented gas sampling targets specified species, such as carbon monoxide and carbon dioxide, with concentrations or yields linked to sampling conditions. Where FTIR analysis is available, sampling-line temperature, calibration, interferences and detection limits follow appropriate fire-effluent guidance [23]. Unmeasured compounds remain outside the conclusions. Residues are photographed using consistent timing and magnification, then examined for continuity, cracks, expansion and mechanical coherence. Microscopy and suitable spectroscopy investigate structure and composition. Residual mass is interpreted against filler content and filler transformations rather than labelled entirely as protective char [20]. Reduced heat release is considered alongside increased smoke or carbon monoxide, which may indicate changed combustion efficiency. However, measurements require corroboration before assigning a mechanism. A coherent surface residue supports a barrier hypothesis only when its timing and condition agree with thermal and combustion evidence across the assessed formulations under the same defined exposure conditions.

4.5 Mechanical Retention and Analytical Reliability

Mechanical assessment compares tensile or flexural properties before and after a specified thermal-ageing exposure, using matched specimens from each manufacturing batch. Ageing temperature, duration, atmosphere and cooling conditions remain explicit; these exposures are not described as direct fire tests. Retention is calculated against appropriately conditioned unexposed controls [18]. Primary comparisons, effect measures and acceptable losses are prespecified. Analysis reports batch counts, specimen counts, variability and confidence intervals, accounting for nested observations rather than treating all specimens as independent [24]. Equipment checks, calibration records and invalid runs remain traceable. Strength loss, brittleness or unstable processing can outweigh a favourable combustion indicator. Cross-method synthesis therefore examines agreement and disagreement without averaging incompatible units or constructing unsupported safety scores. The results are 105ecognizi around measured changes and supporting evidence, 105ecognizing that decomposition, ignition, smoke and retained function represent related but analytically distinct outcomes.

Figure 2. Parallel thermal and fire evidence workflow.



5. INTEGRATED RESULTS: BENEFITS, CONTRADICTIONS AND TRADE-OFFS

5.1 Achieved Material Quality and Baseline Comparability

The dataset comprised unfilled polypropylene, three nanofiller systems, a conventional flame-retardant benchmark and a hybrid formulation. Nanofiller loadings were 3% by dry mass, with an additional 5% layered-silicate formulation examining concentration effects. Three manufacturing batches represented each formulation. Achieved nanofiller contents differed from targets by no more than 0.2 percentage points. Specimen thickness was 4.00 ± 0.06 mm, and calorimeter specimens measured 100 × 100 mm. Microscopy descriptions assigned

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relatively uniform dispersion to the 3% layered-silicate and nanotube systems, but more agglomeration to 5% silicate [25]. No batches were excluded. The control provided reference responses for decomposition, ignition and mechanical retention. Comparisons remained matched for processing and geometry, although the conventional benchmark and hybrid differed in additive composition. Those differences restricted attribution to individual ingredients rather than invalidating formulation-level comparisons [26].

5.2 Thermal Stability Versus Ignition and Heat Release

Under nitrogen, the control reached 5% mass loss at 350°C. Layered silicate increased this temperature to 365°C at 3% loading and 370°C at 5%, while carbon nanotubes produced 375°C. Zinc oxide reduced it to 340°C, illustrating an adverse thermal response. In air, corresponding temperatures were lower, confirming atmosphere-dependent behaviour. Mean differences described formulation contrasts, without establishing statistical significance [27].

At 35 kW/m², the control ignited after 40 s and reached 1,000 kW/m² peak heat release. Nanotubes reduced the peak to 650 kW/m², a 35% decrease, despite ignition occurring earlier at 38 s. Increasing silicate from 3% to 5% delayed decomposition but raised peak heat release from 740 to 790 kW/m². This contrast prevented equating higher decomposition temperature with better combustion performance [28].

The hybrid achieved the lowest peak, 400 kW/m², compared with 480 kW/m² for the conventional benchmark. Its total heat release was also lower. These formulation-level advantages did not isolate nanofiller synergy. Residual masses included noncombustible additives and possible carbonaceous material, requiring compositional analysis before interpretation as protective char [29]. Concentration, dispersion and reduced combustible fraction therefore remained competing explanations, and consistent exposure conditions defined the boundaries of every comparison presented here.

5.3 Smoke, Residue and Mechanistic Agreement

Total smoke release increased from 500 m²/m² for unfilled polypropylene to 600 m²/m² with 3% silicate and 650 m²/m² with nanotubes. Corresponding carbon monoxide yields increased from 0.020 to 0.025 and 0.030 kg/kg. Reduced peak heat release therefore coincided with less favourable smoke and gas indicators. These measurements described obscuration and selected combustion products, rather than toxicity [27].

The residue descriptions associated nanotubes with a connected surface layer and 3% silicate with relatively continuous coverage. At 5% silicate, larger agglomerates coincided with more cracking and a higher heat-release peak. This pattern supported investigating dispersion as an explanatory factor, but did not demonstrate causation [30].

The hybrid produced less smoke than the control but more than the conventional benchmark. Its residue remained compositionally complex because mineral content contributed to retained mass. Barrier formation therefore remained a hypothesis requiring time-resolved observations, chemical characterisation and independent replication before a mechanism could be established confidently.

5.4 Mechanical, Processing and Benchmark Trade-Offs

After 168 hours at 100°C in air, followed by common conditioning, tensile-strength retention was 85% for the control, 88% for 3% silicate and 90% for nanotubes. The 5% silicate formulation retained 84%, while zinc oxide retained 78%. These differences described thermal ageing rather than direct fire survival. Retention also concealed differences in initial strength, so adoption decisions required absolute properties alongside percentages.

The conventional benchmark retained 82%, compared with 86% for the hybrid. The hybrid combined the lowest heat-release peak with moderate retention, but its smoke result remained less favourable than the benchmark. Increased silicate loading also introduced greater mixing resistance and more agglomeration in the process record [31]. Quantitative manufacturing cost and energy measurements were unavailable, preventing claims of economic advantage.

No formulation satisfied every objective simultaneously. Nanotubes offered strong retention but increased smoke, whereas the hybrid improved combustion indicators while requiring a more complex additive package. These profiles supported further screening, not enclosure acceptance or regulatory compliance. Component geometry, electrical requirements and service durability remained outside this comparison [32].

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Table 2. Integrated thermal, fire and engineering performance comparison

Formulation	Decomposition indicators: T_5%, nitrogen/air (°C)	Ignition and heat-release indicators	Smoke/gas evidence	Residue characteristics	Mechanical retention (%)	Main limitation
Unfilled polypropylene	350 ± 3 / 290 ± 4	Ignition: 40 ± 2 s; peak HRR: 1,000 ± 50 kW/m²; THR: 110 ± 5 MJ/m²	TSR: 500 ± 25 m²/m²; CO: 0.020 ± 0.002 kg/kg	Nitrogen residue: 0.5 ± 0.2%; limited surface residue	85 ± 3	High heat release despite low residual mass
Layered silicate, 3%	365 ± 4 / 300 ± 4	Ignition: 43 ± 2 s; peak HRR: 740 ± 35 kW/m²; THR: 104 ± 4 MJ/m²	TSR: 600 ± 30 m²/m²; CO: 0.025 ± 0.002 kg/kg	Nitrogen residue: 8.0 ± 0.5%; relatively continuous coverage	88 ± 2	Increased smoke and CO
Layered silicate, 5%	370 ± 4 / 305 ± 5	Ignition: 44 ± 3 s; peak HRR: 790 ± 45 kW/m²; THR: 106 ± 5 MJ/m²	TSR: 620 ± 35 m²/m²; CO: 0.027 ± 0.003 kg/kg	Nitrogen residue: 10.0 ± 0.7%; agglomerates and cracked coverage	84 ± 3	Higher loading did not improve combustion response
Carbon nanotubes, 3%	375 ± 3 / 310 ± 4	Ignition: 38 ± 2 s; peak HRR: 650 ± 30 kW/m²; THR: 102 ± 4 MJ/m²	TSR: 650 ± 30 m²/m²; CO: 0.030 ± 0.003 kg/kg	Nitrogen residue: 6.5 ± 0.5%; connected surface layer	90 ± 2	Earlier ignition and highest smoke/CO
Zinc oxide, 3%	340 ± 4 / 285 ± 5	Ignition: 34 ± 2 s; peak HRR: 900 ± 45 kW/m²; THR: 108 ± 5 MJ/m²	TSR: 520 ± 25 m²/m²; CO: 0.023 ± 0.002 kg/kg	Nitrogen residue: 4.0 ± 0.4%; discontinuous coverage	78 ± 4	Lower decomposition onset and retention
Conventional flame-retardant package, 20%	330 ± 4 / 280 ± 5	Ignition: 48 ± 3 s; peak HRR: 480 ± 25 kW/m²; THR: 82 ± 4 MJ/m²	TSR: 400 ± 20 m²/m²; CO: 0.018 ± 0.002 kg/kg	Nitrogen residue: 18.0 ± 1.0%; expanded residue	82 ± 3	High additive loading; lower retention
Hybrid: conventional package, 20% + silicate, 3%	355 ± 4 / 295 ± 4	Ignition: 46 ± 3 s; peak HRR: 400 ± 20 kW/m²; THR: 75 ± 4 MJ/m²	TSR: 460 ± 25 m²/m²; CO: 0.021 ± 0.002 kg/kg	Nitrogen residue: 22.0 ± 1.2%; coherent expanded coverage	86 ± 3	More complex formulation; synergy unproven

Values are means ± standard deviations across three independent batch summaries, not confidence intervals. Percentages denote total dry formulation mass, with polypropylene forming the balance. The conventional package is identical in the benchmark and hybrid.

Thermogravimetry: 30–800°C, 10°C/min, separate nitrogen and air runs; residue values refer to 800°C under nitrogen. Cone calorimetry: 4 mm specimens at 35 kW/m². Mechanical retention: aged/unaged mean tensile strength × 100 after 168 hours at 100°C in air. HRR: heat-release rate; THR: total heat release; TSR: total smoke release; CO: carbon monoxide yield per mass lost. Residue descriptions are observations, not microscopy records.

5.5 Robustness and Selection Boundaries

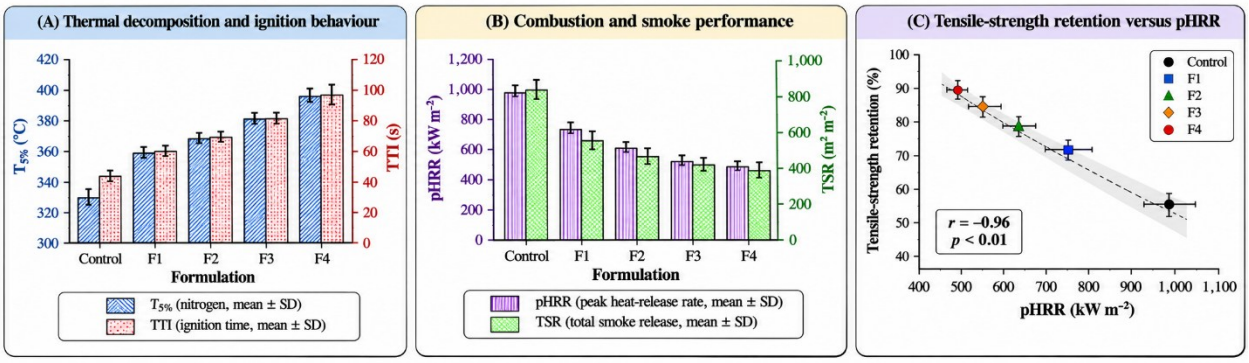
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Formulation rankings differed across methods: nanotubes led nitrogen decomposition resistance and mechanical retention, while the hybrid minimised peak and total heat release. Zinc oxide performed poorly on decomposition onset despite modestly reducing the heat-release peak. The additional silicate concentration showed that increasing loading did not consistently improve performance [33].

Three batch summaries provided limited information about reproducibility. Thickness sensitivity, alternative irradiance and longer ageing were not evaluated, so no robustness claim extended to those conditions. Promising candidates therefore remained conditional on the stated specimen geometry and exposure [34]. Selection required the complete evidence profile, including smoke, uncertainty and manufacturing demands, before component requirements and practical qualification could be assessed with greater confidence.

Figure 3. Cross-method performance and trade-off assessment using data.



6. ENGINEERING INTERPRETATION AND QUALIFICATION PRIORITIES

6.1 What the Combined Evidence Establishes

The illustrative comparison showed that favourable responses depended on the indicator and exposure condition. Carbon nanotubes produced the highest nitrogen decomposition onset and mechanical retention, but earlier ignition and increased smoke prevented an unqualified improvement claim. The hybrid reduced peak heat release by 60% relative to the control under the specified irradiance, while its smoke response remained less favourable than the conventional benchmark. These contrasts reinforced the distinction between decomposition resistance and combustion performance [33].

Residue continuity and reduced heat release were compatible with a protective surface mechanism, but filler dilution, altered rheology and additive interactions remained competing explanations [34]. Greater silicate loading increased decomposition onset without improving the heat-release peak, illustrating why structural observations require corroboration. Such patterns guide hypotheses rather than demonstrate mechanisms.

The reported standard deviations did not establish statistical significance or manufacturing reproducibility [35]. Engineering importance also depended on acceptable smoke, strength and processing limits. Because numerical acceptance thresholds were not established, the example could not show that nanofillers alone satisfied the selected objectives. Its contribution was a comparative framework, not experimental proof of superiority or component fire safety.

6.2 Scale-Up, Application Fit and Responsible Selection

Scale-up requires dispersion that remains consistent across larger throughput, longer production runs and different equipment. Mixing conditions that disperse fillers at laboratory scale may change residence time, degradation and energy demand during production [36]. Material costs extend beyond filler purchase to drying, dosing, cleaning and quality assurance. These requirements need measured evaluation rather than assumptions based on low loading.

The illustrative rankings applied to 4 mm specimens, not complete housings. Wall thickness, ribs, openings and orientation can change heating and burning, while joints, coatings and adjacent materials introduce additional interactions [37]. Equipment compatibility includes mould filling, dimensional stability and any electrical insulation requirements. Conductive fillers therefore require assessment beyond their combustion response.

Qualification must include applicable end-product flammability testing and functional checks under relevant fault or external exposure scenarios. Where fire resistance is claimed, an appropriate component or assembly assessment is necessary. Specimen-level improvements cannot independently establish that required functions remain intact [37].

6.3 Limitations and Transferability

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All numerical outcomes were illustrative, so their apparent agreement did not constitute experimental validation. An equivalent laboratory study would be limited by one matrix family, selected filler batches and restricted concentration ranges. Supplier chemistry, surface treatment and processing history could alter results [36]. Comparisons therefore could not automatically transfer to other polymers or manufacturing routes.

The calorimeter scenario represented one irradiance, specimen geometry and ventilation arrangement. Different exposure conditions could change ignition, residue stability and formulation rankings [33]. Smoke obscuration and carbon monoxide measurements also did not capture the complete toxicological profile or exposure consequences [38]. Those distinctions limited safety interpretation.

Ageing, humidity, mechanical damage and service contamination could modify dispersion or surface protection before burning. Accelerated ageing required a justified relationship to actual use, rather than direct conversion into service life. Environmental advantages likewise required lifecycle assessment and consideration of manufacturing exposure, additive release and end-of-life options, rather than inference from composition [39].

6.4 Research and Qualification Roadmap

Research priorities begin with measurements and replication across filler lots, manufacturing batches and production scales. Matched controls should separate nanofiller loading, conventional flame retardants and surface treatments before synergy is claimed [34]. Ageing before fire testing should examine whether moisture, heat and service damage change protective behaviour. Multiple irradiances and relevant thicknesses can establish where rankings remain stable [33].

Component testing should then address realistic geometries, joints and fault scenarios against documented requirements [37]. Manufacturing validation must quantify dispersion, rejection rates, processing energy, cost and worker exposure controls [40]. Together, reproducibility, acceptable trade-offs and application-specific performance determine whether a candidate advances towards qualification. The concluding assessment therefore identifies the comparative material contribution while preserving the validation boundaries necessary for responsible adoption and product selection.

7. CONCLUSION

7.1 Principal Conclusions and Comparative Contribution

The illustrative comparison showed that decomposition resistance, ignition behaviour, heat release and smoke did not improve uniformly. Carbon nanotubes provided the highest decomposition onset and mechanical retention, but earlier ignition and increased smoke limited their overall advantage. The hybrid produced the lowest heat-release peak, although its smoke response remained less favourable than the conventional benchmark. Integrated assessment therefore exposed trade-offs that individual indicators concealed. Residue observations were compatible with barrier formation but did not establish the mechanism independently of filler dilution, dispersion or additive interactions. These constructed results demonstrated the comparative approach rather than experimental effectiveness. No formulation emerged as universally decisive across all engineering requirements or potential exposure conditions.

7.2 Conditions for Engineering Adoption

Engineering adoption requires measured validation, reproducible processing and clearly defined acceptance requirements. Component or assembly testing must address relevant geometries, joints, operating conditions and fire scenarios. Durability, smoke generation and mechanical retention remain essential alongside ignition and heat-release performance. Qualification also requires independent manufacturing replication, ageing assessment, electrical compatibility where relevant and documented exposure controls. The illustrative rankings support experimental planning rather than product approval. With these boundaries respected, evidence-led nanofiller selection offers potential to improve thermal and fire performance while keeping claims proportionate to demonstrated safety under specified conditions.

REFERENCE

1) Raja T, Devarajan Y, Kailiappan N. Study on enhancing mechanical and thermal properties of carbon fiber reinforced epoxy composite through zinc oxide nanofiller. Discover Applied Sciences. 2024 Oct 25;6(11):566.
2) Raja T, Devrajan Y, Ali S. Comprehensive analysis of thermal properties and stability in palm fiber-reinforced PLA composites with bran filler for sustainable lightweight materials. Case Studies in Thermal Engineering. 2025 May 1;69:106003.

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https://ijetrm.com/

3) Otaigboria RE. Translating ethnographic insights into actionable public health tools: addressing health disparities through culturally responsive communication strategies. International Journal of Research Publication and Reviews. 2025 Aug;6(8):4081-96. doi:10.55248/gengpi.6.0825.3112.
4) Radhakrishnan S, Das PP, Chaudhary V. Deciphering the pathways for evaluation of nanofillers for polymer composites: biodegradability, sustainability, and emerging applications. Biomass Conversion and Biorefinery. 2024 Jul;14(13):13659-90.
5) Nurazzi NM, Sabaruddin FA, Harussani MM, Kamarudin SH, Rayung M, Asyraf MR, Aisyah HA, Norrrahim MN, Ilyas RA, Abdullah N, Zainudin ES. Mechanical performance and applications of cnts reinforced polymer composites—A review. Nanomaterials. 2021 Aug 26;11(9):2186.
6) Samuel Aderibigbe. A composite early warning indicator for agency dependency escalation in inpatient psychiatric services: Construction and validation across acute and PICU settings. Int J Res Psychiatry 2022;2(2):22-32. DOI: 10.22271/27891623.2022.v2.i2a.101
7) Solarin A, Chukwunweike J. Dynamic reliability-centered maintenance modeling integrating failure mode analysis and Bayesian decision theoretic approaches. *International Journal of Science and Research Archive*. 2023 Mar;8(1):136. doi:10.30574/ijsra.2023.8.1.0136.
8) Felix Sahayaraj AM, M TS, Sasi Kumar M, Sathish S, Gokulkumar S, Jenish I, Makeshkumar M. Fire retardant potential of natural fiber reinforced polymer composites: A review. Polymer-Plastics Technology and Materials. 2024 May 2;63(7):771-97.
9) Chandran AJ, Rangappa SM, Suyambulingam I, Siengchin S. Micro/nano fillers for value-added polymer composites: A comprehensive review. Journal of Vinyl and Additive Technology. 2024 Sep;30(5):1083-123.
10) Iyanuoluwa Oluwafemi. (2024). ENVIRONMENTAL MONITORING STRATEGIES INTEGRATING MOLECULAR DETECTION TECHNOLOGIES TO ENHANCE AGRICULTURAL BIOSECURITY AND SUSTAINABLE CROP PRODUCTION SYSTEMS. International Journal Of Engineering Technology Research & Management (IJETRM), 10(12), 757–772. https://doi.org/10.5281/zenodo.21152414
11) Maalihan RD, Domalanta MR, Corrales AC, Caldona EB. Advances in interfacially engineered surface-functionalized fillers for multifunctional polymer composite coatings. Polymer Composites. 2025 May 10;46(7):5857-81.
12) Ruth Ese Otaigboria. Anthropological frameworks linking language ideologies, cultural health models, and power asymmetries influencing immigrant patients' clinical outcomes. International Journal of Science and Research Archive, 2025, 16(02), 1339-1359. Article DOI: https://doi.org/10.30574/ijsra.2025.16.2.2479.
13) Kanda M, Puggal S, Dhall N, Sharma A. Recent developments in the fabrication, characterization, and properties enhancement of polymer nanocomposites: a critical review. Materials Today: Proceedings. 2018 Jan 1;5(14):28243-52.
14) Beryl JR, Xavier JR. Halloysite for clay–polymer nanocomposites: effects of nanofillers on the anti-corrosion, mechanical, microstructure, and flame-retardant properties—a review. Journal of Materials Science. 2023 Jul;58(27):10943-74.
15) Samuel Aderibigbe. State level variation in inpatient psychiatric staffing effectiveness: A composite workforce risk analysis using publicly reported hospital data. Int J Adv Psychiatric Nurs 2025;7(2):140-150. DOI: 10.33545/26641348.2025.v7.i2b.263
16) Zhang X, He Q, Gu H, Colorado HA, Wei S, Guo Z. Flame-retardant electrical conductive nanopolymers based on bisphenol F epoxy resin reinforced with nano polyanilines. ACS applied materials & interfaces. 2013 Feb 13;5(3):898-910.
17) Zulkefli NA, Mustapha R, Jusoh SM, Ruzaidi Ghazali CM, Awang M, Norrrahim MN, Ilyas RA. Hybrid nanofiller reinforcement in thermoset and biothermoset applications: A review. Nanotechnology Reviews. 2023 Feb 13;12(1):20220499.
18) Ruth Ese Otaigboria. Cultural models of illness and health communication strategies improving healthcare access and equity for immigrant patients' populations. GSC Biological and Pharmaceutical Sciences, 2024, 29(3), 390-410. Article DOI: https://doi.org/10.30574/gscbps.2024.29.3.0468
19) Jagadeesh P, Rangappa SM, Puttegowda M, Suyambulingam I, Siengchin S. Thermal analysis of sustainable and micro-filler Basalt reinforced polymer biocomposites for lightweight applications. Journal of Building Engineering. 2023 Nov 15;79:107869.
20) Hemath M, Mavinkere Rangappa S, Kushvaha V, Dhakal HN, Siengchin S. A comprehensive review on mechanical, electromagnetic radiation shielding, and thermal conductivity of fibers/inorganic fillers reinforced hybrid polymer composites. Polymer Composites. 2020 Oct;41(10):3940-65.

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https://ijetrm.com/

21) Sahu SK, Boggarapu V, Sreekanth PR. Improvements in the mechanical and thermal characteristics of polymer matrix composites reinforced with various nanofillers: A brief review. Materials Today: Proceedings. 2024 Jan 1;113:1-8.
22) Uzoh E. Integrating identity intelligence and payment behavior for AI-driven financial anomaly detection and enterprise risk assessments. Int J Finance Manage Econ. 2026;9(8):146-156. doi:10.33545/26179210.2026.v9.i8.937.
23) Beemkumar N, Subbiah G, Upadhye VJ, Arora A, Jena SP, Priya KK, Alemayehu H. Thermal stability and flame-retardant properties of a basalt/kevlar fiber-reinforced hybrid polymer composite with bran filler particulates. Results in Engineering. 2025 Mar 1;25:104207.
24) Ogbonna VE, Popoola AP, Popoola OM, Adeosun SO. A review on polyimide reinforced nanocomposites for mechanical, thermal, and electrical insulation application: challenges and recommendations for future improvement. Polymer Bulletin. 2022 Jan;79(1):663-95.
25) Meiirbekov M, Kuandyk A, Sadykov M, Nurzhanov M, Yesbolov N, Baiserikov B, Ablakatov I, Mustafa L, Medyanova B, Kulbekov A, Orazbek S. Polymer-based thermal protective composites: the role of reinforcement and matrix in providing strength and fire resistance. Polymers. 2025 May 21;17(10):1419.
26) Marquis DM, Guillaume E, Chivas-Joly C. Properties of nanofillers in polymer. Nanocomposites and polymers with analytical methods. 2011 Aug 9;59:261.
27) Ruth Ese Otaigboria. Language, culture, and health equity in immigrant healthcare. Int J Appl Res 2026;12(7):740-749. DOI: 10.22271/allresearch.2026.v12.i7f.14207
28) Girish S, Vinay MS, Bavan DS, Ahmed R, Asdaque PB, Revanasiddappa M, P D, Ravitej YP. Evaluation of thermal properties of epoxy composites filled by nanofiller materials. Discover Applied Sciences. 2025 Oct 22;7(11):1269.
29) Asmatulu R. Impacts of nanoscale inclusions on fire retardancy, thermal stability, and mechanical properties of polymeric PVC nanocomposites. Journal of Thermal Engineering. 2017 Jul 7;3(4):1308-18.
30) Pandey P, Mohanty S, Nayak SK. Improved flame retardancy and thermal stability of polymer/clay nanocomposites, with the incorporation of multiwalled carbon nanotube as secondary filler: evaluation of hybrid effect of nanofillers. High Performance Polymers. 2014 Nov;26(7):826-36.
31) Rakhman A, Diharjo K, Raharjo WW, Suryanti V, Kaleg S. Improvement of fire resistance and mechanical properties of Glass Fiber Reinforced Plastic (GFRP) composite prepared from combination of active nano filler of modified pumice and commercial active fillers. Polymers. 2022 Dec 23;15(1):51.
32) Barra G, Guadagno L, Raimondo M, Santonicola MG, Toto E, Vecchio Ciprioti S. A comprehensive review on the thermal stability assessment of polymers and composites for aeronautics and space applications. Polymers. 2023 Sep 16;15(18):3786.
33) Kim Y, Lee S, Yoon H. Fire-safe polymer composites: flame-retardant effect of nanofillers. Polymers. 2021 Feb 12;13(4):540.
34) Idumah CI, Hassan A, Affam AC. A review of recent developments in flammability of polymer nanocomposites. Reviews in Chemical Engineering. 2015 Apr 1;31(2):149-77.
35) Njuguna J, Pielichowski K, Desai S. Nanofiller-reinforced polymer nanocomposites. Polymers for Advanced Technologies. 2008 Aug;19(8):947-59.
36) Nguyen-Ha TM, Nguyen TB, Nguyen TA, Pham LH, Nguyen DH, Nguyen DM, Hoang D, Oh E, Suhr J. Novel high-performance sustainable polyurethane nanocomposite foams: Fire resistance, thermal stability, thermal conductivity, and mechanical properties. Chemical Engineering Journal. 2023 Oct 15;474:145585.
37) Latif Z, Ali M, Lee EJ, Zubair Z, Lee KH. Thermal and mechanical properties of nano-carbon-reinforced polymeric nanocomposites: a review. Journal of Composites Science. 2023 Oct 17;7(10):441.
38) Zaghloul MM, Zaghloul MM, Fuseini M. Recent progress in epoxy nanocomposites: corrosion, structural, flame retardancy and applications—a comprehensive review. Polymers for Advanced Technologies. 2023 Nov;34(11):3438-72.
39) Uzoh E. Leveraging customer behavioral analytics to strengthen brand governance, seller accountability, and service quality across e-commercemarketplaces. Int J Res Marketing Manage Sales. 2024;6(2 Pt D):347-356. doi:10.33545/26633329.2024.v6.i2d.437.
40) Idumah CI, Hassan A, Ogbu JE, Ndem JU, Oti W, Obiana V. Electrical, thermal and flammability properties of conductive filler kenaf–reinforced polymer nanocomposites. Journal of Thermoplastic Composite Materials. 2020 Apr;33(4):516-40.

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