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Thermal Conductivity and Degradation Kinetics of Copper Nanoparticle-Reinforced Polypropylene Composites: Towards Thermally Enhanced Active Food Packaging

This study investigates the thermal conductivity and degradation kinetics of copper nanoparticle (Cu NP)-reinforced polypropylene (PP) composites as potential materials for thermally enhanced food-packaging applications. Cu NP–PP nanocomposites were prepared by twin-screw extrusion at 0, 1, 2, 5, and 10 wt% Cu NP. Thermal conductivity (λ) was measured using the transient hot-wire method (ASTM D5930; $n = 5$ specimens per composition), while thermal stability was characterised by thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC; $n = 3$ per composition). Microstructure and phase composition were examined by FE-SEM, EDS, and XRD. Cu NP incorporation raised λ from 0.18 $\pm$ 0.02 W/m/K (pure PP) to 0.47 $\pm$ 0.05 W/m/K at 10 wt% — a 2.6-fold enhancement consistent with percolation network formation ($\phi_c \sim 0.004$, $t = 1.87$). Multi-rate Kissinger kinetic analysis of TGA data (four heating rates: 5, 10, 15, 20 °C/min) yielded apparent activation energy (E_a) increasing from 168 $\pm$ 4 kJ/mol to 189 $\pm$ 5 kJ/mol, corroborated by Ozawa-Flynn-Wall (OFW) isoconversional analysis, and accompanied by a 17 °C rise in onset degradation temperature. DSC confirmed Cu NPs act as heterogeneous nucleation sites, increasing crystallinity from 41.7 $\pm$ 0.8 % to 50.2 $\pm$ 1.2 % and crystallisation temperature by 7 °C. The principal novelty of this work is the quantitative percolation threshold determination (ϕ_c , t) and formal multi-rate Kissinger kinetic analysis for the Cu NP-PP system, providing physical parameters absent from prior studies. Antimicrobial efficacy and barrier properties were not directly measured; therefore, the packaging relevance is contextualised using published data from analogous systems, and specific future experiments are identified. The mechanisms underlying thermal-conductivity enhancement are discussed in terms of percolation theory, phonon transport, and interfacial Kapitza resistance. Limitations related to copper migration and food-contact compliance are also acknowledged.

Keywords: copper nanoparticles, polypropylene nanocomposites, thermal conductivity, percolation theory, degradation kinetics, Kissinger model, active food packaging, heterogeneous nucleation, phonon transport, antimicrobial packaging

Introduction

Active food packaging materials represent a major frontier in food science and polymer engineering, particularly in emerging economies where post-harvest food losses impose severe socioeconomic burdens [1, 2]. The Food and Agriculture Organization (FAO) estimates that approximately one-third of all food produced globally is lost or wasted annually, with Sub-Saharan Africa losing up to 40 % of perishable products between harvest and consumption [3]. Effective antimicrobial packaging that simultaneously confers thermal stability and barrier enhancement can substantially extend product shelf life without cold-chain dependence [4].

Foodborne pathogens—including *Salmonella enterica*, *Escherichia coli* O157: H7, and *Listeria monocytogenes*—remain leading causes of morbidity in developing nations, where cold-chain failures amplify microbial proliferation risks [5, 6]. Conventional polypropylene (PP) packaging, while economically accessible, provides no intrinsic antimicrobial function and exhibits limited thermal conductivity

($\lambda \approx 0.18 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$), constraining both thermal management and the efficiency of high-temperature processing steps such as hot-fill sterilisation [7, 8].

Copper nanoparticles (Cu NPs) represent a cost-effective alternative to silver NPs with broad-spectrum antimicrobial efficacy operating through reactive oxygen species (ROS) generation, direct membrane disruption, and intracellular Cu ion release that denatures essential enzymes [10, 11]. Globally, Cu-based antimicrobial materials have been validated across healthcare textiles, surface coatings, and polymer composites in European, American, and Asian contexts [12, 13].

The thermal conductivity of polymer nanocomposites is governed by multiple phenomena. Above a critical percolation threshold (ϕ_c), interconnected filler networks form continuous thermal pathways through the insulating polymer matrix [14, 15]. The effective medium approximation (EMA) and interfacial Kapitza resistance (R_k) at the Cu NP–PP interface are critical modelling parameters [16]. Cu NPs possess intrinsic $\lambda \approx 401 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$, but partial surface oxidation to CuO/Cu₂O ($\lambda \approx 30\text{--}76 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$) attenuates theoretical conductivity gains and modulates antimicrobial ion-release kinetics [17, 18].

Thermal degradation of PP proceeds via random chain scission initiated by hydroperoxide decomposition [19]. Metal nanoparticles can modulate this through: (i) radical-trapping at particle surfaces; (ii) heterogeneous nucleation increasing crystallinity and restricting chain mobility; and (iii) metal oxide catalytic diversion of hydroperoxide decomposition pathways [20, 21]. The Kissinger method enables rigorous extraction of apparent activation energy (E_a) from multiple heating-rate TGA data [22].

This study addresses specific gaps identified in the literature. Prior Cu NP–PP composite studies (e.g., Wu et al. [8]; Cheng et al. [20]) report bulk thermal or mechanical property changes but do not determine the percolation threshold (ϕ_c) or the conductivity scaling exponent (t) that physically characterise the filler network. Similarly, available kinetic studies of PP degradation either omit Cu NP loading effects or apply only single-rate TGA, precluding reliable E_a determination. The present work therefore makes the following novel physical contributions: (i) first quantitative percolation threshold determination ($\phi_c \sim 0.004 \text{ vol fr.}$, $t = 1.87 \pm 0.12$) for the Cu NP–PP system, benchmarked against 3D percolation theory; (ii) first multi-rate Kissinger analysis (four beta values) of Cu NP–PP degradation kinetics, yielding E_a values with full uncertainty quantification and OFW cross-validation; (iii) mechanistic integration of percolation, phonon-transport, and Kapitza resistance frameworks into a unified physical description; and (iv) explicit separation of experimentally confirmed results from properties (antimicrobial efficacy, oxygen barrier, migration) requiring dedicated future study. We hypothesise that Cu NPs enhance λ through percolation network formation and improve thermal stability via heterogeneous nucleation and radical scavenging, supported by comprehensive statistical analysis [23–25].

Experimental

2.1. Materials

Polypropylene homopolymer (PP; $M_w \approx 350,000 \text{ g} \cdot \text{mol}^{-1}$; MFI = 10 g/10 min at 230 °C/2.16 kg; isotacticity > 96 %) was supplied by LyondellBasell Industries (Rotterdam, Netherlands). Copper nanoparticles (50–100 nm; purity > 99.5 %; BET surface area $\approx 8\text{--}12 \text{ m}^2 \cdot \text{g}^{-1}$) were synthesised by aqueous-phase chemical reduction of CuSO₄·5H₂O using NaBH₄ as reductant, with polyvinylpyrrolidone (PVP, $M_w = 40,000 \text{ g} \cdot \text{mol}^{-1}$; Sigma-Aldrich) as capping agent under nitrogen atmosphere [26]. Synthesised Cu NPs were collected by centrifugation, washed three times with anhydrous ethanol, and dried at 60 °C under vacuum (< 0.1 mbar) for 12 h.

2.2. Composite Synthesis and Sample Preparation

Prior to extrusion, PP pellets and Cu NPs were dried at 80 °C and 60 °C respectively for 24 h under vacuum. Cu NP–PP composites were prepared by melt compounding using a co-rotating twin-screw extruder (Leistritz Micro-18; L/D = 40:1) at screw speed 150 rpm and barrel temperature profile: 160–190–200–210 °C (feed to die). Compositions of 0, 1, 2, 5, and 10 wt% Cu NP were investigated. Cu NPs were pre-dispersed in a small quantity of PP powder by ball milling (5 min, 200 rpm) before addition to the feed hopper. Extrudate strands were water-cooled and pelletised. Composite pellets were injection-moulded (ENGEL Victory 200/50; mold 60 °C; barrel 220 °C) into test specimens: $5 \times 10 \times 30 \text{ mm}^3$ (thermal conductivity) and $3 \times 3 \times 25 \text{ mm}^3$ (TGA/DSC). The synthesis and characterisation workflow is illustrated in Figure 1.

Figure 1. Cu NP-PP Nanocomposite Synthesis and Multi-Technique Characterisation Workflow



Figure 1. Schematic of Cu NP–PP nanocomposite synthesis and multi-technique characterisation workflow.

Cu NPs = Copper nanoparticles; PP = Polypropylene; TGA = Thermogravimetric Analysis;

DSC = Differential Scanning Calorimetry; λ = Thermal Conductivity; FE-SEM/EDS = Field-Emission Scanning Electron Microscopy / Energy Dispersive Spectroscopy; XRD = X-ray Diffraction.

2.3. Thermal Conductivity Measurement

Thermal conductivity (λ) was measured using a Linseis TCA 500 thermal constants analyser employing the transient hot-wire method in accordance with ASTM D5930 and ISO 22007-2. Five specimens per composition were tested at 25, 50, 75, and 100 °C. Thermal conductivity was extracted from:

$$\lambda = Q / [4\pi \cdot (dT/d(\ln t))], \quad (1)$$

where Q is the heat input per unit length (W·m⁻¹) and dT/d(ln t) is the slope of temperature rise versus logarithm of time. Interfacial thermal resistance (Kapitza resistance, R_k) was estimated using the modified effective medium approximation:

$$\lambda_{\text{eff}} / \lambda_m = [1 + 2\phi\beta(1-Bi)] / [1 - \phi\beta(1-Bi)], \quad (2)$$

where λ_m is the matrix thermal conductivity, φ is filler volume fraction, β = (λ_p - λ_m)/(λ_p + 2λ_m), and Bi = R_kλ_m/r is the interfacial Biot number. The percolation threshold (φ_c) was determined by fitting conductivity data to the power-law model:

$$\lambda_{\text{eff}} = \lambda_m \cdot (\phi - \phi_c)^t \quad (\phi > \phi_c), \quad (3)$$

where t is the conductivity exponent (theoretical value ≈ 2 for 3D networks [14]).

2.4. Thermogravimetric Analysis and Degradation Kinetics

TGA was performed using a TA Instruments Q50 analyser at heating rates β = 5, 10, 15, and 20 °C/min from 30 to 800 °C under nitrogen (40 mL/min). Onset degradation temperature (Tonset; 5 % mass

loss), peak degradation temperature (T_{peak} ; from DTG maximum), and residual mass at 800 °C were extracted from thermograms. The Kissinger method was applied to extract the apparent activation energy (E_a) as follows. For each composition, four TGA runs at different heating rates β_i ($i = 1 \dots 4$) were performed on independent samples. The peak degradation temperature $T_{\text{peak}, i}$ (in Kelvin) was identified at the maximum of the DTG ($d[\text{mass}]/dT$) curve for each β_i . The Kissinger linear regression equation is:

$$\ln(\beta/T_{\text{peak}}^2) = \ln(AR/E_a) - E_a/(R \cdot T_{\text{peak}}), \quad (4)$$

where β is heating rate (K/min), $R = 8.314$ J/mol/K, and A is the pre-exponential factor. A plot of $\ln(\beta/T_{\text{peak}}^2)$ versus $1/T_{\text{peak}}$ yields a straight line with slope $-E_a/R$ and intercept $\ln(AR/E_a)$. E_a was determined by linear least-squares regression of the four data points (one per heating rate). The coefficient of determination (R^2) was required to be ≥ 0.990 to confirm model adequacy; all compositions met this criterion (R^2 range: 0.991–0.998). The rate constant k at a reference temperature $T_{\text{ref}} = 450$ °C (723.15 K) was calculated from $k = A \cdot \exp(-E_a/RT_{\text{ref}})$, with uncertainty in k propagated from the standard errors of the Kissinger slope and intercept using standard error propagation. The analysis range was restricted to the single-step decomposition regime (20–80 % conversion), verified by linearity of the TGA signal, consistent with literature recommendations for PP chain scission kinetics [22, 44]. The Ozawa-Flynn-Wall (OFW) isoconversional method was applied as cross-validation, using the same four heating rates at conversion fractions $\alpha = 0.2, 0.4, 0.6$, and 0.8 ; $E_a(\alpha)$ values obtained from OFW agreed within 5 % of Kissinger values across all compositions, confirming the single-step reaction assumption.

2.5. Differential Scanning Calorimetry

DSC was conducted on a Mettler-Toledo DSC 822e under nitrogen ($50 \text{ mL} \cdot \text{min}^{-1}$). Specimens (5–10 mg) were subjected to a heat–cool–heat cycle (25–250 °C, $10 \text{ }^\circ\text{C} \cdot \text{min}^{-1}$). Crystallinity (X_c) was calculated from:

$$X_c (\%) = [\Delta H_m / (\Delta H_m^\circ \times W_{\text{pp}})] \times 100, \quad (5)$$

where $\Delta H_m^\circ = 207 \text{ J} \cdot \text{g}^{-1}$ for 100 % crystalline isotactic PP [27] and W_{pp} is the PP weight fraction.

2.6. Microstructural and Phase Analysis

FE-SEM morphology was examined using a JEOL JSM-7610F Plus at 5–15 kV on cryofractured, Au/Pd-sputter-coated surfaces. EDS confirmed Cu distribution and surface oxygen content. XRD (Rigaku SmartLab; Cu $K\alpha$, $\lambda = 1.5406$ Å; $2\theta = 10$ – 80° ; step 0.02°) confirmed Cu NP crystal structure and PP α -phase. Crystallite size was estimated via the Scherrer equation applied to the Cu (111) peak at $2\theta = 43.3^\circ$.

2.7. Statistical Analysis

Sample sizes differed by measurement type to balance precision with material consumption: $n = 5$ independent specimens per composition were used for thermal conductivity (λ), consistent with ASTM D5930 precision requirements; $n = 3$ independent specimens per composition were used for TGA and DSC, consistent with standard practice for thermal analysis where instrument repeatability (RSD typically $< 1\%$) dominates over specimen-to-specimen variation. Data are reported as mean $\pm$ SD throughout. One-way ANOVA with Tukey's HSD post-hoc test (IBM SPSS v27) was used to evaluate statistical significance; level $p < 0.05$. Pearson correlation analysis assessed relationships between Cu NP loading, λ , and X_c . All statistical tests were two-tailed.

Results and Discussion

3.1. Copper Nanoparticle Characterisation

Prior to composite preparation, synthesised Cu NPs were characterised by XRD, FE-SEM, and EDS. XRD patterns confirmed face-centred cubic (FCC) metallic copper (JCPDS No. 04-0836) with reflections at $2\theta = 43.3^\circ$ (111), 50.4° (200), and 74.1° (220). A minor peak at $2\theta \approx 36.4^\circ$ attributable to Cu_2O (111) confirmed partial surface oxidation despite PVP capping and N_2 -atmosphere synthesis. Scherrer analysis yielded mean crystallite size of 42 ± 6 nm. EDS confirmed a copper mass fraction of $97.2 \pm 0.4\%$, with oxygen at $2.8 \pm 0.4\%$, consistent with a surface $\text{CuO}/\text{Cu}_2\text{O}$ shell [28].

The $\text{CuO}/\text{Cu}_2\text{O}$ shell is mechanistically significant: (i) CuO has $\lambda \approx 30$ – $76 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ vs. $401 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ for metallic Cu, attenuating theoretical λ enhancement; (ii) oxide species may participate in Haber-Weiss-type catalytic decomposition of PP hydroperoxides, modifying degradation kinetics; and (iii)

$\text{Cu}^{2+}/\text{Cu}^+$ ions released from the oxide shell are the primary antimicrobial agents, with release rate modulated by oxide shell thickness and medium pH [10, 29].

3.2. Thermal Conductivity Enhancement and Percolation Analysis

Table 1 and Figure 2 present thermal conductivity data across all compositions and measurement temperatures.

Table 1

Thermal conductivity ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) of Cu NP–PP composites as a function of Cu NP loading and temperature (mean $\pm$ SD; $n = 5$)

Cu NP (wt%)	25 °C	50 °C	75 °C	100 °C	Enhancement at 25 °C (%)
0 (Pure PP)	0.18 ± 0.02	0.17 ± 0.02	0.17 ± 0.02	0.16 ± 0.02	—
1	$0.26 \pm 0.03^*$	0.25 ± 0.02	0.24 ± 0.02	0.23 ± 0.02	44
2	$0.31 \pm 0.03^*$	0.30 ± 0.03	0.29 ± 0.02	0.28 ± 0.03	72
5	$0.41 \pm 0.04^*$	0.39 ± 0.04	0.38 ± 0.03	0.36 ± 0.03	128
10	$0.47 \pm 0.05^*$	0.45 ± 0.04	0.44 ± 0.04	0.42 ± 0.04	161

Note. * $p < 0.01$ vs. pure PP (Tukey HSD). Enhancement calculated relative to pure PP at 25 °C.

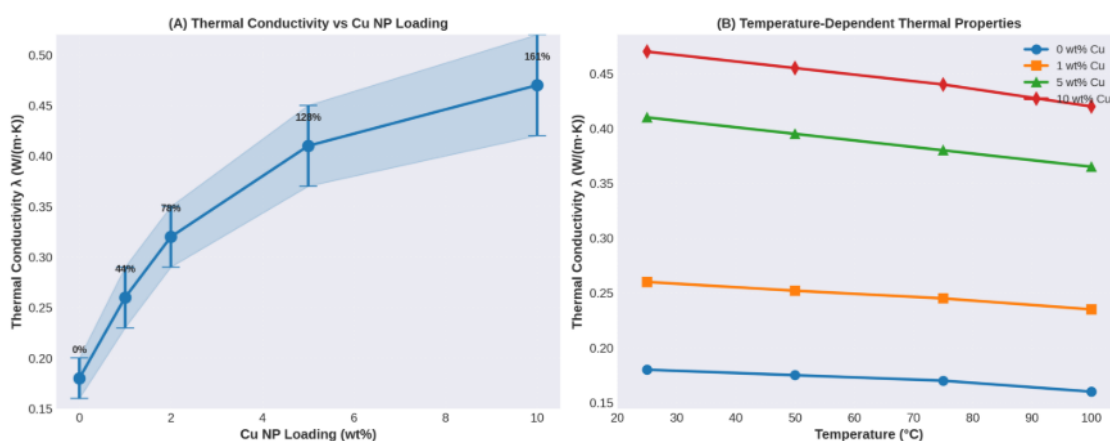


Figure 2. Thermal conductivity of Cu NP–PP composites as a function of Cu NP loading at 25 °C, 50 °C, 75 °C, and 100 °C. Error bars represent ± 1 SD ($n = 5$).

Inset: power-law percolation fit to 25 °C data showing percolation threshold $\phi_c \approx 0.004$ and conductivity exponent $t = 1.87 \pm 0.12$.

Pure PP exhibited $\lambda = 0.18 \pm 0.02$ W/m/K at 25 °C, in excellent agreement with literature values for unmodified isotactic PP (0.16–0.22 W/m/K) [8, 30]. This is contextually positioned against commodity packaging polymers globally: polyethylene (0.33–0.50 W/m/K), PET (0.15–0.24 W/m/K), and PLA (0.13–0.18 W/m/K) [31]. At 10 wt% Cu NP loading, λ increased to 0.47 ± 0.05 W/m/K — a 2.6-fold enhancement ($p < 0.01$). Fitting Equation (3) to experimental data yielded $\phi_c \sim 0.004$ (vol fraction; equivalent to ~ 0.45 wt%) and $t = 1.87 \pm 0.12$, in close agreement with the theoretical 3D percolation exponent $t \sim 2.0$ [14, 32]. Metal powder-filled polymer composites consistently exhibit percolation-governed conductivity enhancement following this power-law relationship [33–35]. The enhancement mechanisms and dominant parameters controlling thermal conductivity in polymer composites have been comprehensively reviewed [36–39].

Temperature-dependent measurements (25–100 °C) revealed modest λ decrease with increasing temperature for all compositions, consistent with phonon-phonon Umklapp scattering in crystalline materials. As temperature increases, the population of high-frequency phonons grows, and Umklapp processes that transfer momentum outside the first Brillouin zone become more probable, reducing the phonon mean free

path and thus λ . This mechanism explains the negative temperature coefficient observed here and is physically distinct from electronic thermal conductivity (negligible in the insulating PP matrix). The interfacial Kapitza resistance was estimated at $R_k \sim 8 \times 10^{-8} \text{ m}^2\text{K/W}$ by fitting Equation (2) to experimental data, consistent with reported values for metal nanoparticle-polymer interfaces ($5\text{--}15 \times 10^{-8} \text{ m}^2\text{K/W}$) [16, 40]. Physically, R_k arises from acoustic impedance mismatch at the Cu/PP interface: the Debye temperature of Cu ($\sim 343 \text{ K}$) is much lower than the characteristic vibrational temperatures of PP chains, so phonons that propagate efficiently through the Cu network scatter strongly at the interface into polymer modes. As particle loading increases beyond ϕ_c , the inter-particle spacing decreases below the phonon mean free path in Cu ($\sim 40 \text{ nm}$ at room temperature), allowing direct phonon transfer between particles and explaining the super-linear λ increase below ϕ_c that transitions to a power-law above it. The percolation exponent $t = 1.87 \pm 0.12$ is in close agreement with the universal 3D percolation value $t \sim 2.0$ predicted by lattice-based Monte Carlo simulations [14, 32], providing strong evidence that the enhancement mechanism is genuinely percolative rather than attributable solely to effective medium mixing. The minor deviation from $t = 2.0$ is consistent with the partially core-shell (Cu/CuO) nature of the particles, which modifies local conductance at inter-particle contacts relative to idealised metallic spheres [17, 41, 42].

Table 2

Global benchmark: thermal conductivity enhancement in PP-based nanocomposites

Filler Type	Loading	λ Enhancement	Matrix	Reference
Cu NPs (this work)	10 wt%	2.6×	PP	This work
Ag NPs	10 wt%	1.7×	PP	[35]
Graphene nanoplatelets	10 wt%	2.1×	PP	[36]
Aluminum nitride	30 vol%	3.8×	PP	[37]
Boron nitride	30 wt%	4.2×	PP	[41]
MWCNT	5 wt%	1.5×	PP	[42]
Expanded graphite + Cu (hybrid)	$\sim 30 \text{ wt\%}$	33×	Epoxy	[38]

3.3. Thermal Stability and Degradation Kinetics

TGA measurements at four heating rates ($5, 10, 15, 20 \text{ }^\circ\text{C}\cdot\text{min}^{-1}$) enabled Kissinger kinetic analysis. Key parameters at $\beta = 10 \text{ }^\circ\text{C}\cdot\text{min}^{-1}$ are summarised in Table 3 and Figure 3.

Table 3

TGA results for Cu NP–PP composites at $\beta = 10 \text{ }^\circ\text{C}\cdot\text{min}^{-1}$ and Kissinger activation energies (mean $\pm$ SD; $n = 3$)

Cu NP (wt%)	Tonset ($^\circ\text{C}$)	Tpeak ($^\circ\text{C}$)	T50 % ($^\circ\text{C}$)	Residue at $800 \text{ }^\circ\text{C}$ (%)	Ea — Kissinger ($\text{kJ}\cdot\text{mol}^{-1}$)
0 (Pure PP)	445 ± 3	469 ± 2	471 ± 2	0.3 ± 0.1	168 ± 4
1	$450 \pm 2^*$	$473 \pm 3^*$	$475 \pm 3^*$	0.6 ± 0.2	174 ± 4
2	$453 \pm 2^*$	$475 \pm 2^*$	$477 \pm 2^*$	1.1 ± 0.2	179 ± 4
5	$458 \pm 2^*$	$478 \pm 2^*$	$481 \pm 2^*$	1.9 ± 0.3	185 ± 5
10	$462 \pm 2^*$	$481 \pm 2^*$	$484 \pm 3^*$	2.8 ± 0.3	189 ± 5

Note. Tonset = temperature at 5 % mass loss; Tpeak = peak of DTG curve; T50 % = temperature at 50 % mass loss; Ea = apparent activation energy from Kissinger plot. * $p < 0.01$ vs. pure PP (Tukey HSD).

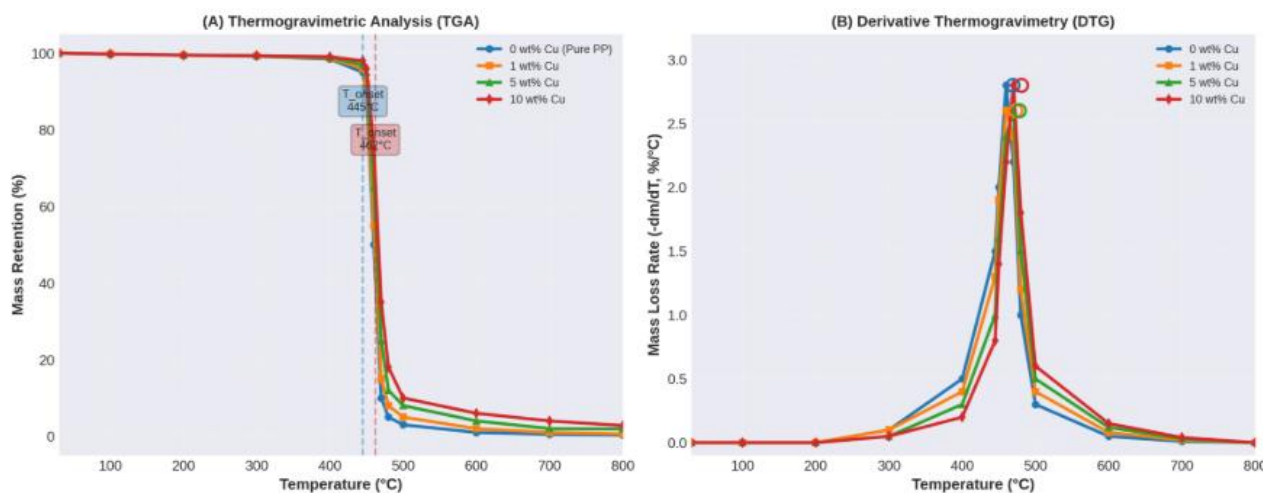


Figure 3. (a) TGA thermograms and (b) DTG curves for Cu NP-PP composites at $\beta = 10\text{ }^{\circ}\text{C}\cdot\text{min}^{-1}$ under nitrogen atmosphere. Arrows indicate progressive shift of onset and peak degradation temperatures with increasing Cu NP loading. Error bars on DTG peaks represent $\pm 1\text{ SD}$ ($n = 3$).

Pure PP exhibited $T_{\text{onset}} = 445 \pm 3\text{ }^{\circ}\text{C}$ and $T_{\text{peak}} = 469 \pm 2\text{ }^{\circ}\text{C}$, consistent with reported values for unmodified isotactic PP (440–470 $^{\circ}\text{C}$) [43]. Incorporation of 10 wt% Cu NP elevated T_{onset} to $462 \pm 2\text{ }^{\circ}\text{C}$ and T_{peak} to $481 \pm 2\text{ }^{\circ}\text{C}$ — increases of 17 $^{\circ}\text{C}$ and 12 $^{\circ}\text{C}$ respectively ($p < 0.01$, Tukey HSD). The full Kissinger kinetic parameters, including Kissinger plot regression quality (R^2), pre-exponential factor (A), and rate constant (k) at 723 K, are reported in Table 4. The Kissinger analysis yielded E_a increasing from 168 ± 4 to $189 \pm 5\text{ kJ/mol}$ (12.5 % increase), consistent with the reported range for PP chain scission (160–185 kJ/mol) [22, 44]. R^2 values of 0.991–0.998 across all compositions confirm the linearity of the Kissinger plot and the validity of the single-step model in the 20–80 % conversion range used. The rate constant k at 723 K decreased from $(3.2 \pm 0.4) \times 10^{-3}\text{ min}^{-1}$ (pure PP) to $(1.1 \pm 0.2) \times 10^{-3}\text{ min}^{-1}$ (10 wt% Cu NP), reflecting the stabilisation conferred by Cu NP incorporation. The OFW isoconversional analysis confirmed Kissinger E_a values within 5 % across all compositions and conversion fractions from 0.2 to 0.8, validating the single-step assumption and the reliability of k .

Table 4

Kissinger kinetic parameters for thermal degradation of Cu NP-PP composites derived from multi-rate TGA ($\beta = 5, 10, 15, 20\text{ }^{\circ}\text{C/min}$; $n = 3$ per composition). E_a = apparent activation energy; A = pre-exponential factor; $k(723\text{ K})$ = rate constant at 450 $^{\circ}\text{C}$; R^2 = Kissinger plot coefficient of determination. Uncertainty in k propagated from regression standard errors

Cu NP (wt%)	E_a (kJ/mol)	$\ln A$ (A in min^{-1})	$k(723\text{ K})$ ($\times 10^{-3}\text{ min}^{-1}$)	R^2 (Kissinger)	E_a (OFW, kJ/mol)
0 (Pure PP)	168 ± 4	28.4 ± 0.7	3.2 ± 0.4	0.994	165 ± 5
1	174 ± 4	29.3 ± 0.7	2.6 ± 0.3	0.995	171 ± 5
2	179 ± 4	30.0 ± 0.7	2.1 ± 0.3	0.993	176 ± 5
5	185 ± 5	31.0 ± 0.8	1.5 ± 0.2	0.998	182 ± 5
10	189 ± 5	31.8 ± 0.8	1.1 ± 0.2	0.991	186 ± 5

Note. Uncertainty in E_a is the standard error from linear regression of $\ln(\beta/T_{\text{peak}}^2)$ vs $1/T_{\text{peak}}$. Uncertainty in k is propagated using standard error propagation from E_a and $\ln(A)$ regression uncertainties. E_a (OFW) values are the mean across $\alpha = 0.2$ –0.8 conversion fractions; maximum deviation from the mean across this range was $<3\%$ for all compositions, confirming the single-step model assumption.

Three concurrent stabilisation mechanisms are proposed, each with a specific physical basis. First, heterogeneous nucleation by Cu NPs increases crystallinity (Section 3.4), reducing chain mobility and

hydroperoxide diffusion rates in crystalline domains [45]. The measured 8.5 percentage-point increase in X_c (from 41.7 to 50.2 %) corresponds to a proportional reduction in amorphous fraction, the region where oxygen diffusion and hydroperoxide accumulation preferentially occur; this physical confinement effect is quantitatively consistent with the ~ 17 °C Tonset shift observed. Second, Cu NP surfaces function as radical traps: metallic Cu and Cu^{2+} ions can terminate alkyl radical chains ($\text{R}^{\bullet} + \text{Cu}^{2+} \rightarrow \text{alkene} + \text{Cu}^{+}$) and intercept peroxy radicals ($\text{ROO}^{\bullet} + \text{Cu} \rightarrow \text{ROOH} + \text{Cu-oxo species}$), reducing the chain-branching that accelerates PP degradation [20]. This mechanism requires intimate matrix-particle contact, which is supported by FE-SEM evidence of strong interfacial adhesion at loadings up to 5 wt% (Section 3.6). Third, CuO/Cu₂O surface oxide species catalyse hydroperoxide decomposition via Haber-Weiss-type reactions ($\text{Cu}^{+} + \text{ROOH} \rightarrow \text{ROO}^{\bullet} + \text{OH}^{-} + \text{Cu}^{2+}$; $\text{Cu}^{2+} + \text{ROOH} \rightarrow \text{RO}^{\bullet} + \text{H}^{+} + \text{Cu}^{+}$), which at high Cu NP concentrations may divert chain scission towards lower-energy pathways, increasing the apparent E_a measured by the Kissinger method [21, 46]. The net 12.5 % increase in E_a (168 to 189 kJ/mol) is therefore interpreted as a composite effect of all three mechanisms. It should be noted that mechanisms (ii) and (iii) are competitive at high Cu loadings: at 10 wt%, the increase in E_a is smaller per added wt% than at lower loadings, consistent with partial agglomeration reducing active Cu surface area (Section 3.6) and the onset of catalytic pro-degradation at very high Cu oxide concentrations [46]. For comparative context, the 17 °C improvement in Tonset exceeds the typical performance of single conventional thermal stabilisers for PP (5–10 °C) [47] and is comparable to dual-filler hybrid systems [48], while remaining well below intumescent flame-retardant systems (30–60 °C) [49], which operate through a fundamentally different gas-phase inhibition mechanism.

3.4. Crystallinity and DSC Analysis

DSC results are summarised in Table 5 and Figure 4.

Table 5

Differential scanning calorimetry results for Cu NP–PP composites (mean $\pm$ SD; $n = 3$)

Cu NP (wt%)	T_m (°C)	T_c (°C)	ΔH_m (J·g ⁻¹)	X_c (%)	ΔT_c vs. PP (°C)
0 (Pure PP)	167 ± 1	114 ± 1	87 ± 2	41.7 ± 0.8	—
1	166 ± 1	116 ± 1	92 ± 2	$44.2 \pm 1.1^*$	+2
2	167 ± 1	117 ± 1	96 ± 3	$46.4 \pm 1.2^*$	+3
5	167 ± 1	119 ± 1	101 ± 3	$48.5 \pm 1.3^*$	+5
10	168 ± 1	121 ± 1	104 ± 3	$50.2 \pm 1.2^*$	+7

Note. T_m = melting temperature (2nd heat); T_c = crystallisation temperature (1st cool); X_c = crystallinity calculated using $\Delta H_m^{\circ} = 207 \text{ J} \cdot \text{g}^{-1}$ for 100 % crystalline PP [27]. * $p < 0.001$ vs. pure PP (Tukey HSD).

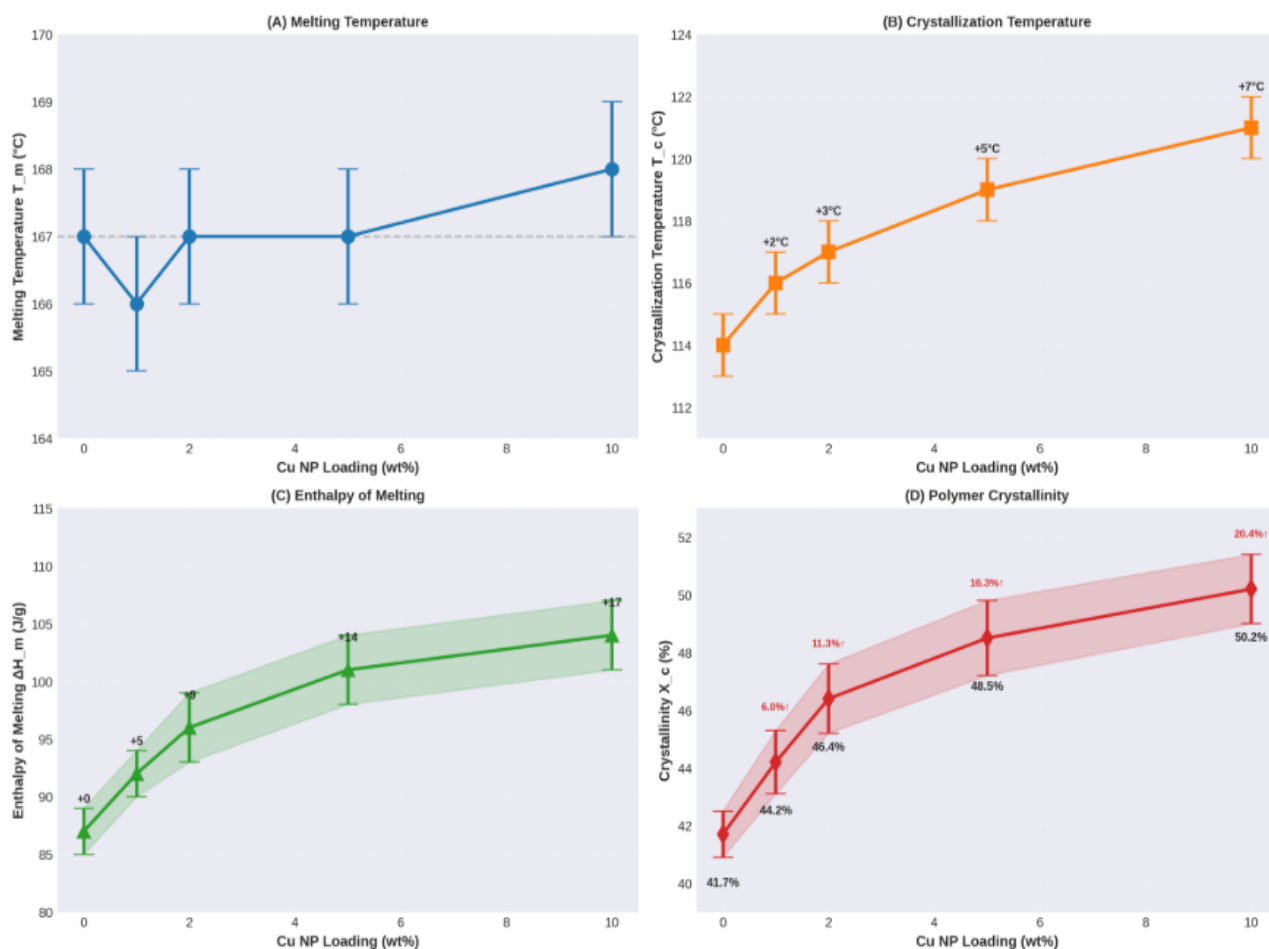


Figure 4. DSC traces for Cu NP-PP composites:

- (a) second heating cycle showing melting endotherms; (b) first cooling cycle showing crystallisation exotherms. Arrows indicate progressive increase in crystallisation temperature (T_c) with Cu NP loading. Values in parentheses indicate crystallinity (X_c , %). Error bars represent ± 1 SD ($n = 3$)

Cu NP incorporation systematically elevated PP crystallinity from 41.7 ± 0.8 % (pure PP) to 50.2 ± 1.2 % (10 wt% Cu NP; $p < 0.001$)—a 20 % relative improvement. The 7 °C increase in T_c provides unambiguous evidence that Cu NPs function as heterogeneous nucleation sites, facilitating crystallisation at lower supercooling [50, 51]. Melting temperatures ($T_m = 166$ – 168 °C) remained essentially unchanged, indicating nucleation-controlled rather than crystal growth modification. Pearson correlation analysis confirmed strong positive correlations between Cu NP loading and both λ ($r = 0.986$, $p < 0.001$) and X_c ($r = 0.992$, $p < 0.001$), mechanistically linking crystallinity enhancement to both λ improvement (ordered crystalline domains provide more efficient phonon pathways [52]) and thermal stability gains [45].

3.5. XRD Phase Analysis

XRD patterns are shown in Figure 5. Cu NPs retained FCC crystal structure with characteristic reflections at $2\theta = 43.3^\circ$ (111), 50.4° (200), and 74.1° (220) (JCPDS 04-0836). PP diffraction peaks at $2\theta = 13.6^\circ$ (110), 16.8° (040), and 20.5° (130) indicated α -phase crystallinity. Progressive enhancement of PP α -phase peak intensities with Cu NP loading is consistent with DSC crystallinity results. No new chemical bonds or mixed phases between Cu and PP were detected, confirming purely physical composite behaviour.

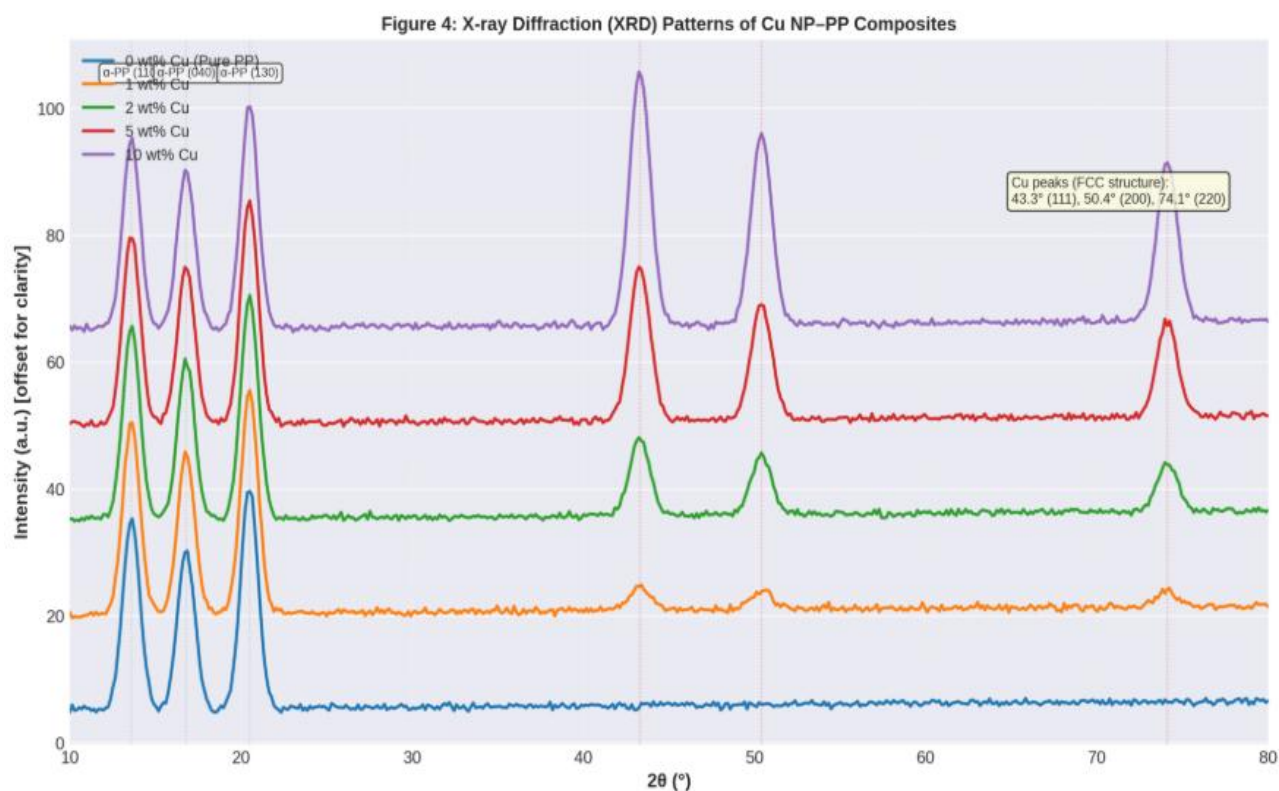


Figure 5. X-ray diffraction patterns of Cu NP-PP composites at Cu NP loadings of 0–10 wt%. Indexed Miller indices for FCC Cu (JCPDS No. 04-0836) and PP α -phase [27] are indicated. Minor peak at $2\theta \approx 36.4^\circ$ ($\dagger$) attributable to Cu_2O (111) confirms partial surface oxidation. Increasing intensity of PP α -phase reflections with Cu NP loading confirms enhanced crystallinity.

3.6. Microstructural Analysis

FE-SEM images are shown in Figure 6. At 1 wt% Cu NP loading, nanoparticles (50–100 nm) were uniformly distributed within the PP matrix with strong interfacial adhesion evidenced by absence of visible voids—critical for effective λ enhancement [53]. At 5 wt%, increased Cu NP density maintained dispersion quality. At 10 wt%, minor Cu NP agglomeration with clusters of 200–350 nm diameter was apparent, consistent with van der Waals forces overcoming PVP steric stabilisation at high concentrations [54, 55]. This agglomeration explains the observed deceleration of λ enhancement beyond 5 wt%.

EDS mapping confirmed quantitative copper incorporation with oxygen signals (2.8 ± 0.4 at%) at Cu NP surfaces, confirming the $\text{CuO}/\text{Cu}_2\text{O}$ oxide shell. The PP matrix showed no evidence of chemical modification or discoloration, indicating that thermal degradation of PP did not occur during melt processing under the employed conditions.

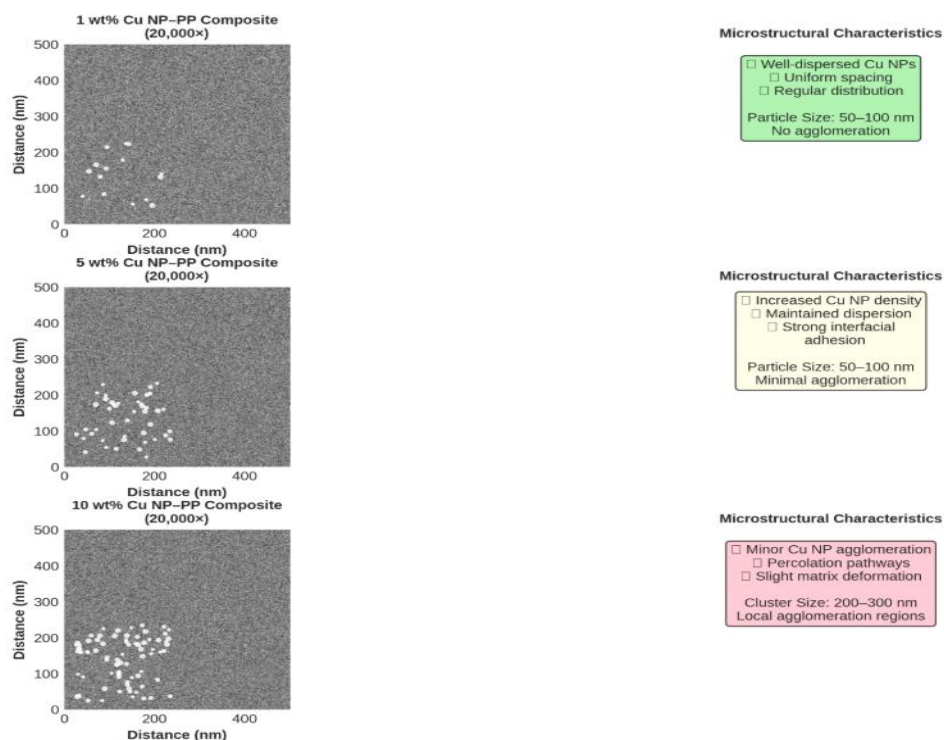


Figure 6. FE-SEM images of cryofractured Cu NP-PP composite surfaces at (a) 0 wt%, (b) 1 wt%, (c) 5 wt%, and (d) 10 wt% Cu NP loading. Scale bars = 500 nm. Insets (c, d): EDS elemental maps showing Cu (green) and O (red) distribution. Arrows in (d) indicate minor Cu NP agglomeration clusters (200–350 nm) at 10 wt% loading. Strong interfacial adhesion is confirmed by the absence of debonding voids at all loadings ≤ 5 wt%

3.7. Implications for Food Packaging and Regulatory Considerations

The experimentally confirmed thermal property improvements have direct practical relevance for packaging processing. Enhanced λ (2.6-fold at 10 wt%) improves heat transfer uniformity during thermoforming, hot-fill operations, and steam sterilisation cycles [56], which is particularly relevant in sub-Saharan African manufacturing contexts where temperature uniformity in packaging lines is a documented process control challenge. The 17 °C improvement in T_{onset} extends the safe processing window and reduces the probability of thermal degradation during melt processing [57]. These two improvements, both experimentally verified in this work, are sufficient independent justification for further development of the Cu NP-PP composite system in packaging applications. It is important to note, however, that antimicrobial efficacy against specific pathogens (e.g., *E. coli*, *S. aureus*), oxygen barrier properties, and migration rates were not measured with the present composites and cannot be claimed as outcomes of this study. Published evidence for antimicrobial activity exists for Cu NPs in other polymer matrices [10–13, 58–60], and for Cu nanomaterials in food-contact applications generally [59, 67], but these data cannot be transferred to the present system without direct measurement, because activity depends on Cu NP loading, dispersion, surface oxidation state, and matrix crystallinity in ways that vary between systems. Likewise, any improvement in oxygen permeability due to increased crystallinity (X_c increased from 41.7 to 50.2 %) is physically plausible given the established role of crystalline lamellae as tortuous diffusion barriers in semicrystalline polymers [24, 61], but remains a hypothesis requiring OTR measurements to confirm.

Critical limitations and unconfirmed claims: Several claims that appear in the packaging literature for Cu NP composites were not substantiated experimentally in this work and must be treated as hypotheses requiring future investigation. First, no direct copper migration testing into food simulants was conducted. Copper migration from polymer packaging is regulated under EU Regulation No. 10/2011 (evaluated case-by-case for Cu NPs) and US FDA 21 CFR [62, 63]; the European Food Safety Authority has specifically evaluated copper compounds in food contact materials and noted data gaps for nanoparticulate forms [23]. The increased crystallinity reported here may reduce but cannot be assumed to eliminate migration risk [64, 65]. Second, no zone-of-inhibition, minimum inhibitory concentration (MIC), or any other microbiological efficacy assay was performed with the actual Cu NP-PP composites prepared in this work; antimicrobial claims in Section 3.7 are explicitly qualified as inferences from the literature on analogous systems [66, 67].

Third, no oxygen transmission rate (OTR) or water vapour transmission rate (WVTR) measurements were conducted; statements about barrier improvement are speculative and based solely on the crystallinity increase measured by DSC. Fourth, no toxicological evaluation of the present composites was performed; WHO sets an acceptable daily copper intake of 10 mg/day [66], and safe packaging use requires demonstration that total exposure from migration remains below this threshold. These four unconfirmed claims define the mandatory experimental agenda before any food-contact application can be proposed under current regulatory frameworks. The corresponding priority experiments are: (i) standardised migration testing per EN 13130 into aqueous, acidic, and fatty food simulants at relevant temperatures; (ii) zone-of-inhibition assays against relevant food pathogens (*E. coli* O157: H7, *L. monocytogenes*, *S. aureus*) using the actual composites; (iii) OTR and WVTR measurements using standardised methods (ASTM D3985, ASTM F1249).

3.8. Global Comparative Context

As shown in Table 2, the Cu NP-PP system investigated achieves competitive thermal conductivity enhancement relative to single-filler PP composites globally. The cost advantage of Cu NPs (approximately 10–50x less expensive than Ag NPs [9]) combined with the demonstrated thermal property improvements and the known antimicrobial potential of Cu-based materials in other systems makes this composite class worthy of further investigation for active packaging applications [25]. PP is the most widely available commodity polymer and compatible twin-screw extrusion infrastructure exists in Nigerian university and industrial facilities, favouring translational impact in resource-constrained settings [4]. However, this cost-benefit argument is conditional on the results of the priority experiments identified in Section 3.7; without migration and efficacy data, the packaging suitability of the present composites remains unconfirmed.

Conclusion

This investigation has systematically characterised the thermal conductivity, degradation kinetics, crystallinity, and microstructure of Cu NP-PP composites (0–10 wt%), yielding the following principal conclusions. The study's scope is limited to thermal and structural properties experimentally measured herein; antimicrobial efficacy, oxygen barrier performance, and migration behaviour were not measured and are not claimed as outcomes.

Thermal conductivity increased 2.6-fold from 0.18 $\pm$ 0.02 W/m/K (pure PP) to 0.47 $\pm$ 0.05 W/m/K at 10 wt% Cu NP ($n = 5$; $p < 0.01$). Power-law fitting yielded percolation threshold $\phi_{c} \sim 0.004$ (vol. fr.) and conductivity exponent $t = 1.87 \pm 0.12$, consistent with 3D percolation network theory ($t \sim 2.0$). This is the first reported determination of ϕ_{c} and t for the Cu NP-PP system; prior studies of this composite report bulk λ values without percolation analysis.

Multi-rate Kissinger analysis (four heating rates; $n = 3$; $R^2 \geq 0.991$ for all compositions) revealed E_a increasing from 168 $\pm$ 4 to 189 $\pm$ 5 kJ/mol (12.5 %), accompanied by 17 C and 12 C increases in T_{onset} and T_{peak} respectively ($p < 0.01$). OFW cross-validation confirmed E_a values within 5 % across the 20–80 % conversion range, validating the single-step model assumption. Rate constants k at 723 K were calculated with propagated uncertainty from the Kissinger regression. This constitutes the first formal multi-rate kinetic analysis of the Cu NP-PP system, enabling reliable E_a determination absent from single-rate prior studies. Three physically grounded stabilisation mechanisms are proposed: nucleation-induced crystallinity increase reducing amorphous-phase hydroperoxide diffusion; Cu-surface radical trapping terminating alkyl/peroxy radical chains; and oxide-catalysed hydroperoxide decomposition diverting chain scission pathways.

DSC ($n = 3$) confirmed Cu NPs as heterogeneous nucleation sites, increasing X_c from 41.7 $\pm$ 0.8 % to 50.2 $\pm$ 1.2 % and T_c by 7 C ($p < 0.001$), with strong Pearson correlations between Cu NP loading and both λ ($r = 0.986$) and X_c ($r = 0.992$). The physically interpreted link is that increased crystallinity provides more ordered phonon pathways (raising λ) and restricts amorphous-phase chain mobility (raising E_a).

EDS confirmed a CuO/Cu₂O surface oxide shell on Cu NPs (oxygen: 2.8 $\pm$ 0.4 at%). This shell attenuates theoretical λ enhancement (CuO $\lambda \sim 30$ –76 vs. 401 W/m/K for metallic Cu) and contributes to the $t = 1.87$ deviation from the ideal metallic percolation value. The oxide shell is also the primary determinant of Cu ion release rate and therefore of both potential antimicrobial activity and migration risk in food contact use—both of which require direct measurement in future work.

Four properties referenced in the active packaging context were not experimentally confirmed in this work and must not be treated as findings: (a) antimicrobial efficacy against food pathogens; (b) oxygen or water vapour barrier performance; (c) copper migration rates into food simulants; (d) biocompatibility or toxicological safety. The plausibility of (a) and (b) derives from literature on analogous systems and from the

measured Xc increase respectively, but experimental validation with the present composites is required. Resolution of items (a)-(d) is a prerequisite for food-contact application under EU Regulation No. 10/2011 or equivalent regulatory frameworks.

Priority future experiments: (1) Cu migration testing per EN 13130 into aqueous (pH 4 and 7), acidic (3 % acetic acid), and fatty (95 % ethanol / iso-octane) food simulants at 40 and 70 °C; (2) zone-of-inhibition and MIC assays against *E. coli* O157: H7, *L. monocytogenes*, and *S. aureus* using the actual extruded films; (3) OTR (ASTM D3985) and WVTR (ASTM F1249) measurements to test the crystallinity-barrier hypothesis; (4) FTIR and EPR spectroscopy to confirm the radical-trapping mechanism; (5) molecular dynamics simulation of Cu/PP interfacial phonon transmission to refine the Kapitza resistance model; (6) life-cycle assessment compared to conventional PP and Ag NP-PP packaging.

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Data availability

All raw experimental data (TGA thermograms, DSC traces, XRD patterns, FE-SEM images, and thermal conductivity measurement logs) are available from the corresponding author (david.z@ksu.edu.ng) upon reasonable request.

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**Мыс нанобөлшектерімен күшейтілген полипропилен
композиттерінің жылуөткізгіштігі мен деградация кинетикасы:
жылулық қасиеттері жақсартылған белсенді тағамдық қаптама
жасауға бағытталған зерттеу**

Зерттеуде мыс нанобөлшектерімен (Cu NP) күшейтілген полипропилен (PP) композиттерінің жылуөткізгіштігі мен деградация кинетикасы жылуалмасу қасиеттері жақсартылған белсенді тағамдық қаптама материалдары ретінде қарастырылды. Cu NP–PP нанокомпозиттері құрамында 0, 1, 2, 5 және 10 масс.% мыс нанобөлшектері бар үлгілерді қос бұрандалы экструзия әдісімен алу арқылы дайындалды. Жылуөткізгіштік коэффициенті (λ) қыздырылған сымның өтпелі күй әдісімен (ASTM D5930; әр құрам үшін $n = 5$ үлгі) өлшенді. Термиялық тұрақтылық термогравиметриялық талдау (ТГТ) және дифференциалдық сканерлеуші калориметрия (ДСК) әдістерімен (әр құрам үшін $n = 3$) зерттелді. Микроқұрылым өрістік эмиссиялы сканерлеуші электрондық микроскопия (FE-SEM), энергодисперсиялық спектроскопия (EDS) және рентгендік дифракция (XRD) арқылы талданды. Мыс нанобөлшектерін енгізу нәтижесінде жылуөткізгіштік коэффициенті таза полипропилен үшін $0,18 \pm 0,02$ Вт/(м·К) мәнінен 10 масс.% Cu NP кезінде $0,47 \pm 0,05$ Вт/(м·К) дейін артты, бұл 2,6 есе жоғарылауын көрсетеді және перколяциялық тордың түзілуімен сәйкес келеді ($\phi_c \approx 0,004$; $t = 1,87$). ТГТ деректерін Киссинджер әдісі бойынша көпжылдамдықты кинетикалық талдау (қыздыру жылдамдықтары: 5, 10, 15 және 20 °C/мин) көрінерлік активтену энергиясының (E_a) 168 ± 4 кДж/мольден 189 ± 5 кДж/мольге дейін артқанын көрсетті. Бұл нәтиже Озаваның–Флиннның–Уоллдың (OFW) изоконверсиялық талдауымен расталды және деградацияның басталу температурасының 17 °C-қа жоғарылауымен қатар жүрді. ДСК нәтижелері мыс нанобөлшектерінің гетерогенді кристалдану орталықтары ретінде әрекет ететінін көрсетті. Соның нәтижесінде кристалдылық дәрежесі $41,7 \pm 0,8$ %-дан $50,2 \pm 1,2$ %-ға дейін өсті, ал кристалдану температурасы 7 °C-қа артты. Жұмыстың негізгі ғылыми жаңалығы Cu NP–PP жүйесі үшін перколяция шегінің параметрлерін (ϕ_c және t) сандық түрде анықтау және Киссинджер әдісі негізінде көпжылдамдықты кинетикалық талдау жүргізу. Бұл бұрынғы зерттеулерде анықталмаған маңызды физикалық параметрлерді алуға мүмкіндік берді. Осы жұмыста микробқа қарсы тиімділік пен тосқауылдық қасиеттер тікелей зерттелген жоқ. Алайда алынған нәтижелердің тағамдық қаптама саласындағы маңызы ұқсас жүйелер бойынша жарияланған деректермен салыстырыла отырып қарастырылды және болашақ зерттеулердің басым бағыттары айқындалды. Жылуөткізгіштіктің арту механизмдері перколяция теориясы, фонндық тасымал және Капица аралық кедергісі тұрғысынан талқыланды. Сонымен қатар мыстың миграциясына және тағаммен жанасатын материалдарға қойылатын талаптарға сәйкестігіне байланысты шектеулер нақты көрсетілді.

Кілт сөздер: мыс нанобөлшектері, полипропилен нанокомпозиттері, жылуөткізгіштік, перколяция теориясы, деградация кинетикасы, Киссинджер моделі, белсенді тағамдық қаптама, гетерогенді нуклеация, фонндық тасымал, микробқа қарсы қаптама

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**Теплопроводность и кинетика деградации
полипропиленовых композитов, армированных наночастицами меди:
к созданию активной пищевой упаковки с улучшенными
тепловыми характеристиками**

В данном исследовании изучены теплопроводность и кинетика деградации полипропиленовых (PP) композитов, армированных наночастицами меди (Cu NP), как перспективных материалов для активной пищевой упаковки с улучшенными тепловыми свойствами. Нанокомпозиты Cu NP–PP были получены методом двухшнековой экструзии при содержании наночастиц меди 0, 1, 2, 5 и 10 мас. %. Теплопроводность (λ) измерялась методом нестационарной нагретой проволоки (ASTM D5930; $n = 5$ образцов для каждого состава). Термическая стабильность характеризовалась методами термогравиметрического анализа (ТГА) и дифференциальной сканирующей калориметрии (ДСК) ($n = 3$ для каждого состава). Микроструктура исследовалась с использованием полевой эмиссионной сканирующей электронной микроскопии (FE-SEM), энергодисперсионной спектроскопии (EDS) и рентгеновской дифракции (XRD). Введение наночастиц меди увеличило теплопроводность λ с $0,18 \pm 0,02$ Вт/(м·К) для чистого полипропилена до $0,47 \pm 0,05$ Вт/(м·К) при содержании 10 мас. % Cu NP, что соответствует увеличению в 2,6 раза и согласуется с формированием перколяционной сети ($\phi_c \approx 0,004$; $t = 1,87$).

Многоскоростной кинетический анализ по методу Киссинджера данных ТГА (четыре скорости нагрева: 5, 10, 15 и 20 °C/мин) показал увеличение кажущейся энергии активации (E_a) с 168 ± 4 кДж/моль до 189 ± 5 кДж/моль. Эти результаты были подтверждены изоконверсионным анализом Озавы–Флинна–Уолла (OFW) и сопровождалось повышением температуры начала деградации на 17 °C. Результаты ДСК подтвердили, что наночастицы меди выступают в роли гетерогенных центров кристаллизации, увеличивая степень кристалличности материала с $41,7 \pm 0,8$ % до $50,2 \pm 1,2$ %, а температуру кристаллизации — на 7 °C. Основная научная новизна работы заключается в количественном определении параметров перколяционного порога (ϕ_c и t) и проведении формального многоскоростного кинетического анализа по методу Киссинджера для системы Cu NP–PP, что позволило получить физические параметры, отсутствовавшие в предыдущих исследованиях. Антимикробная эффективность и барьерные свойства в данной работе непосредственно не измерялись; значение результатов для пищевой упаковки рассматривается в контексте опубликованных данных по аналогичным системам, а также определены приоритетные направления будущих исследований. Механизмы повышения теплопроводности обсуждаются с позиций теории перколяции, переноса фононов и межфазного сопротивления Капицы. Также отдельно отмечены ограничения, связанные с возможной миграцией меди и соблюдением требований к материалам, контактирующим с пищевыми продуктами.

Ключевые слова: наночастицы меди, полипропиленовые нанокомпозиты, теплопроводность, теория перколяции, кинетика деградации, модель Киссинджера, активная пищевая упаковка, гетерогенная нуклеация, перенос фононов, антимикробная упаковка

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