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Thermal Properties of Composite Materials: A Systematic Review of Experimental and Theoretical Models

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ABSTRACT

Composite materials offer superior properties compared to their constituents, yet a comprehensive understanding of their thermal behavior requires integrating experimental and theoretical models. This paper systematically reviews these models, employing a rigorous SLR methodology guided by PRISMA to analyze existing research. The review identifies key factors influencing thermal conductivity, compares the strengths and limitations of various models like the rule of mixtures and finite element analysis, and explores the impact of material composition and manufacturing methods. The findings highlight the necessity of combining theoretical predictions with empirical data for optimizing composite material design.

Keywords: Composite Materials, Thermal Properties, Experimental Models, Theoretical Models, Systematic Literature Review.

1. Introduction

Composite materials have revolutionized modern engineering and industry, offering unparalleled advantages in terms of strength, durability, and versatility (Ali & Hassabo, 2024; Ngo, 2020; Madu et al., 2020). These materials, which consist of two or more distinct phases, typically a reinforcement (e.g., fibers, particles) embedded in a matrix (e.g., polymer, metal, ceramic), exhibit properties that are superior to those of their constituents. For instance, carbon fiber-reinforced polymers (CFRPs) are widely used in aerospace applications due to their high strength-to-weight ratio, which significantly reduces fuel consumption and enhances performance (Rafi, 2024 ; Gupta et al., 2022) . Similarly, glass fiber-reinforced composites are employed in the automotive industry to produce lightweight and corrosion-resistant components, contributing to improved fuel efficiency and reduced emissions (Patel et al., 2018; Todor et al., 2017). Beyond mechanical performance, composites also exhibit excellent thermal and electrical properties, making them indispensable in sectors such as renewable energy, electronics, and construction (Haider, 2018; Madu et al., 2019). For example, ceramic matrix composites (CMCs) are used in gas turbines for their ability to withstand extreme temperatures, while polymer composites with conductive fillers are utilized in electromagnetic shielding applications (Shahapurkar et al., 2022). The adaptability of composite materials to meet specific performance requirements has cemented their role as a cornerstone of advanced engineering solutions (Bangari, 2022). Despite the extensive research on composite materials, there remains a significant gap in the literature regarding a comprehensive integration of experimental and theoretical models. Experimental studies provide valuable empirical data on the mechanical, thermal, and electrical properties of composites, but they are often limited by factors such as sample preparation, testing conditions, and scalability. For instance, while tensile testing can accurately measure the strength of a composite, it may not fully capture the anisotropic behavior or failure mechanisms under complex loading conditions (De Luca & Caputo, 2017; Zheng et al., 2023). On the other hand, theoretical models, such as micromechanical analyses and finite element simulations, offer predictive insights into composite behavior but often rely on simplifying assumptions that may not fully reflect real-world complexities (Adams, 1974; Yu et al., 2007). For example, the rule of mixtures, a widely used micromechanical model, assumes perfect bonding between the fiber and matrix, which is rarely achieved in practice (Yao & Huang, 2013; Madu et al., 2019). While numerous studies have explored either experimental or theoretical approaches, there is a lack of comprehensive reviews that critically evaluate and integrate both methodologies. This fragmentation in the literature hinders a holistic understanding of composite material properties and limits the development of optimized design strategies. The objective of this paper is to systematically review and analyze the experimental and theoretical models used to study the properties of composite materials. By employing a systematic literature review (SLR) methodology, this study aims to identify, evaluate, and synthesize the most effective approaches for characterizing and predicting the mechanical, thermal, and electrical behavior of composites. The SLR approach ensures a rigorous and transparent process, minimizing bias and enhancing the reproducibility of the findings. This methodology involves a structured search of peer-reviewed literature, followed by a critical appraisal of the selected studies to extract relevant data and insights. The systematic nature of this review allows for a comprehensive assessment of both established and emerging models, providing a balanced perspective on their applicability and limitations.

2. Research Methodology

The methodology for this study is grounded in a Systematic Literature Review (SLR), a rigorous and structured approach designed to comprehensively analyze existing research on the thermal properties of composite materials. The SLR methodology ensures transparency, minimizes bias, and enhances the reproducibility of findings, making it particularly suitable for synthesizing diverse experimental and theoretical studies. The process is guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, which provides a clear and systematic pathway for identifying, screening, and selecting relevant studies (Moher et al., 2010). The PRISMA flowchart, as illustrated in Figure 1, visually represents the stages of the review process, including identification, screening, eligibility, and inclusion of studies, ensuring a transparent and methodical approach. The literature search was conducted using the Scopus database, a widely recognized and comprehensive abstract and citation database that indexes high-quality peer-reviewed journals and conference proceedings (Rossetto, 2021; Brahme, 2020). Scopus was selected for its extensive coverage of scientific literature, ensuring that the review is based on credible and up-to-date research. The search strategy employed a combination of keywords related to composite materials, thermal properties, experimental models, and theoretical frameworks. Boolean operators (AND, OR) were used to refine the search, ensuring that relevant studies were captured while excluding irrelevant ones. For example, search terms included "composite materials AND thermal conductivity," "experimental models AND theoretical models," and "thermal properties AND finite element analysis." This approach ensured a broad yet focused search, capturing studies that address both experimental and theoretical aspects of thermal conductivity in composites. The initial search yielded a large number of studies, which were then screened based on predefined inclusion and exclusion criteria. The inclusion criteria focused on studies that investigated the thermal properties of composite materials, provided experimental data or theoretical models, were published in peer-reviewed journals or conferences, and were written in English. Studies that did not meet these criteria, such as those focusing solely on mechanical properties or non-composite materials, were excluded. The screening process was conducted in two stages: first, by reviewing titles and abstracts, and second, by assessing the full text of potentially relevant studies. This two-stage screening process ensured that only the most relevant studies were included in the review, as depicted in the PRISMA flowchart (Figure 1). Data extraction was performed using a standardized form, capturing key information such as the type of composite material, experimental methods, theoretical models, and thermal conductivity values. The extracted data were synthesized to identify patterns, trends, and gaps in the literature. The synthesis process involved both qualitative and quantitative analysis, with a focus on comparing experimental results with theoretical predictions. For instance, the rule of mixtures and Halpin-Tsai model were critically evaluated for their accuracy in predicting thermal conductivity (Mennie et al., 2024; Yun et al., 2023). Additionally, the finite element analysis (FEA) and machine learning models were assessed for their ability to simulate complex thermal behaviors in composites (Tong et al., 2022; Shin et al., 2024). To ensure the quality of the included studies, a critical appraisal was conducted using established criteria for evaluating experimental and theoretical research. Studies were assessed based on their methodological rigor, sample size, and the validity of their findings. This step was crucial in ensuring that the review is based on high-quality evidence. The PRISMA flowchart (Figure 1) visually represents the systematic process of identifying, screening, and selecting studies, beginning with the identification of records through database searching, followed by the removal of duplicates and the screening of titles and abstracts. The full-text assessment phase ensures that only studies meeting the eligibility criteria are included, providing a transparent and structured approach to the review process.

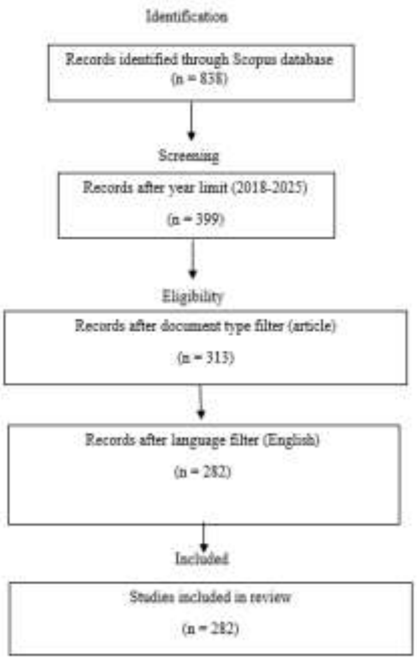

Figure 1: PRISMA Method

3. Results

3.1 Key Factors influencing the thermal conductivity of composite materials

The thermal conductivity of composite materials is influenced by a multitude of factors, which can be broadly categorized into material composition, manufacturing methods, and interfacial properties. One of the primary determinants is the type and properties of the inclusions (e.g., fibers, particles, or fillers) embedded within the matrix. For instance, carbon fibers and carbon nanotubes (CNTs) exhibit high thermal conductivity due to their graphitic structure, making them effective reinforcements for enhancing thermal performance (Mennie et al., 2024; Abaimov et al., 2023). Conversely, glass fibers, while mechanically robust, have lower thermal conductivity, which can limit their effectiveness in thermal management applications (Yun et al., 2023). The orientation and distribution of these inclusions also play a critical role. Aligned fibers, for example, create anisotropic thermal pathways, significantly enhancing conductivity along the alignment axis while limiting it in other directions (Tong et al., 2022). Similarly, the volume fraction of inclusions affects thermal conductivity, with higher filler loading generally leading to improved thermal performance, although this can be offset by increased interfacial thermal resistance (ITR) at higher concentrations (He et al., 2023). The matrix material itself is another critical factor. Polymer matrices, such as epoxy or polypropylene, typically exhibit low thermal conductivity, which can be improved by incorporating conductive fillers like graphene or silver nanowires (Li et al., 2019; He et al., 2023). However, the interfacial thermal resistance between the matrix and the inclusions often limits the overall thermal performance. Phonon scattering at the interfaces, caused by mismatches in thermal properties, can significantly reduce the effective thermal conductivity of the composite (Shi et al., 2020). Strategies to mitigate ITR, such as the use of hybrid fillers or surface functionalization, have shown promise in enhancing thermal conductivity (Cai et al., 2018). Additionally, manufacturing methods like compression molding, pultrusion, and additive manufacturing influence the distribution and alignment of inclusions, thereby affecting thermal pathways. For example, 3D printing allows for precise control over fiber orientation, enabling the creation of optimized thermal pathways, but is often limited by the thermal properties of available materials (Thirugnanasamabandam et al., 2025). Overall, the interplay between material composition, interfacial properties, and manufacturing techniques determines the thermal conductivity of composite materials, with each factor requiring careful consideration in the design and optimization process.

Table 1: Thematic analysis of Key Factors influencing the thermal conductivity of composite materials

Theme	Subtheme	Code	**Quote**	Citation
Material Composition	Inclusion Properties (Type, Conductivity)	Inclusion Type, Inclusion Conductivity, Sediment Type, Sand, Silt, Clay	*"This paper presents a thermal homogenization methodology for the optimization of heat transfer in Gypsum Plaster Boards formulation using dredged marine sediments." "This showed that the dredged sediments are mainly sandy."*	(Abdelaziz et al., 2023)
	Matrix Properties (Type, Conductivity)	Matrix Type, Matrix Conductivity, Gypsum	*"Actually, the present work proposes an innovative way and a feasibility study of their recycling in construction materials as Gypsum Plaster boards"*	
	Volume Fraction & Distribution	Volume Fraction, Distribution	*"ANSYS Finite Element Code is used to numerically compute the effective homogenized thermal conductivity of Gypsum-sediment composite incorporating different volume fractions of sediments."*	
	Fiber Properties (Type, Orientation, Conductivity)	Fiber Type, Fiber Orientation, Fiber Conductivity	*"The interplay between the constituent materials, their morphological arrangement (e.g. shape and distribution of fibers in a composite), and the bonding interfaces or grain boundaries significantly influence the overall thermal and heat transfer mechanisms within these microstructures and therefore thermal conductivity." "During the generation of the training data, we assumed that the thermal conductivity of the matrix is isotropic (km), while the yarns have distinct axial (ka) and transverse (kt) thermal conductivities, respectively."*	(Shin et al., 2024)

	Reinforcement Type & Properties	WoodFlour, Ceramic, WPLA, CPLA	*"Wood flour reinforced PLA (WPLA) is lightweight and biocompatible."*	(Thirugnanasamabandam et al., 2025)
	Matrix Material & Properties	PLA	*"To improve its physical and chemical properties for any intended use, the most promising Polylactic acid (PLA) has recently been copolymerized using other polymeric or non-polymeric components."*	
	Reinforcement Type & Properties	Graphene, Silver Nanowires, AgNWs, High Thermal Conductivity, High Aspect Ratio	*"By introducing AgNWs with a high aspect ratio into graphene, this study constructed a novel multi-dimensional high-k nanofiller composed of one-dimensional (1D) silver nanowires (AgNWs) and two-dimensional (2D) graphene, namely gra@AgNWs."*	(He et al., 2023)
		Defect Remedy, Phonon Transfer	*"The AgNWs decorated could remedy the intrinsic defects of graphene by passing through the interstices within graphene nanosheets to form connections as bridges."*	
	Matrix Material & Properties	Polymer Binder, F2313, CTFE, VDF, Low Thermal Conductivity	*"The low k values of explosive crystals (less than 0.5 W m^{-1} K^{-1}) and polymer binder (less than 0.3 W m^{-1} K^{-1}) severely limit the effective heat dissipation in PBXs, resulting in severe thermal stresses, which impair the environmental adaptability and reliability of PBXs with low mechanical properties by causing cracks or damage."*	
	Interfacial Thermal Resistance (ITR)	ITR, Phonon Scattering, Kapitza Resistance	*"For polymer composites with dispersed high-k fillers, the inevitable and significant phonon scattering, which is caused by the intrinsic structural defects of fillers and the high ITR, accounts for its low enhancement efficiency."*	
	Synergistic Effect	Hybrid Fillers, Multidimensional	*"A commonly adopted synergetic strategy is to utilize fillers of different sizes and/or dimensions to form long thermally conductive pathways and low RC at relatively low filler loading."*	
	Composite Materials	Carbon composites and their thermal behavior	*"Carbon-carbon (C/C) composites are used in the braking systems subjected to severe conditions, when the superficial and volumetric temperatures may exceed respectively 1500°C and 800°C."*	(Yevtushenko et al., 2020)
	Polymer and Metal-Ceramic Materials	Thermal limits of polymer and metal-ceramic materials	*"Polymeric friction materials are used in brake systems operating in relatively light conditions, when the temperature on the contact surface does not exceed 400°C and the volumetric temperature is lower than 300°C."*	
	Composite Materials	Carbon composites and their thermal behavior	*"Carbon-carbon (C/C) composites are preferably employed in high-performance structural parts such as rocket nose cone, wing leading edges of the space shuttle, aircraft and racing car braking shoes pads."*	

	Polymer and Carbon Matrix	Thermal limits of polymer and carbon matrix materials	*"The CCs are usually obtained after three stage processing: In the first stage, the polymer matrix composites (PMCs) are fabricated by impregnation of liquid polymer resin."*	(Kumar et al., 2019)
	Composite Materials	Plaster and clay-based composites	*"The composite building materials of interest in this study are gypsum or clay-based often used in some constructions such as a wall or interior ceiling plaster."*	(Lkouen et al., 2023)
	Additives	Peanut shells and cork as ecological additives	*"The inclusions in the composite material are peanut shells, which constitute an abundant, ecological and unexploited waste."*	
Fiber Type	Carbon Nanotubes (CNTs)	High aspect ratio and thermal conductivity of CNTs	*"For carbon nanotube (CNT)-like particles, computational efficiency would increase multifold if we were able to replace these complex interactions with an equivalent 1D geometry."*	(Abaimov et al., 2023)
	Alignment of CNTs	Anisotropic thermal conductivity	*"In thermal analysis of CNT nanocomposites, thermal conductivity of an effective medium is provided by heat transfer in both matrix and CNT network. The latter is anisotropic in the case of forests."*	
	Influence of Fiber Orientation	Anisotropic structures, Fiber alignment	*"The particles are horizontally aligned or 45° tilted... The multiscale results can reproduce the local temperature and radiation fluctuations due to the elliptical particles."*	(Tong et al., 2022)
	Carbon Fibers	High thermal conductivity	*"Carbon fibers exhibit high thermal conductivity due to their graphitic structure."*	(Mennie et al., 2024)
	Glass Fibers	Low thermal conductivity	*"Glass fibers have lower thermal conductivity compared to carbon fibers."*	
	Natural Fibers	Variability in properties	*"Natural fibers like flax or hemp show variability in thermal conductivity based on moisture."*	
	Ceramic Fibers	High-temperature stability	*"Ceramic fibers, such as SiC, are used in high-temperature applications due to their stability."*	
	Basalt Fibers	High thermal resistance	*"Basalt is a noncombustible material with heat dissipation, heat resistance, and sound insulation properties."*	(Yun et al., 2023)
		Lightweight and high strength	*"Basalt has lightweight high-strength properties, making it suitable for composites."*	
	Multilayer Graphene (MLG)	High thermal conductivity	*"MLG significantly enhances the thermal conductivity of the epoxy matrix material, increasing it by about 553% at 25 wt% load."*	(Li et al., 2019)
	Graphene Oxide (GO)	Moderate thermal conductivity	*"GO/epoxy composites show a thermal conductivity increase of 311% at 25 wt% load."*	
	Carbon Nanotube (CNT)	Synergistic effect with MLG	*"MLG/CNT binary mixed filler forms a 3D heat conduction path, enhancing thermal conductivity."*	

	Alumina Trihydrate (ATH)	Fire retardant and intumescent effect	*"ATH acts as a fire retardant, mostly through the intumescence it induces when it dehydrates, resulting in a thermal barrier effect."*	(Shi et al., 2020)
	Ethylvinyl Acetate (EVA)	Polymer matrix	*"EVA is the polymer matrix in the composite, which decomposes during thermal degradation, leaving no solid residue."*	
	SiO_2 Nanoparticles	SiO_2 nanoparticles are used to modify thermal properties	*"SiO_2 nanoparticles with different average particle sizes (15-20 nm, 20-30 nm, 60-70 nm, 1-5 μm) are used to investigate the mechanisms of the enhancement."*	(Qiao et al., 2019)
	Nanoparticle Size Effect	Smaller nanoparticles have a greater impact on thermal properties	*"The addition of smaller nanoparticles (15-20 nm and 20-30 nm) appears to give a decrease in the melting point of $NaNO_3$."*	
	Carbon Fiber Properties	High thermal conductivity along fiber axis	*"The manufacturer of the carbon fibers provides the thermal conductivity along the fiber axis $K\Theta f\|\| = 17\ Wm^{-1}\ K$…"*	(Tröger & Hartmann, 2022)
	Graphene Nanoplatelets (GNPs)	Ultrahigh thermal conductivity of GNPs	*"Graphene is a kind of two-dimensional layered material with an ultrahigh thermal conductivity of ~5000 $W\ (m\ K)^{-1}$"*	(Cai et al., 2018)
	Boron Nitride (BN)	High thermal conductivity and anisotropy of BN	*"BN seems the most promising, owing to its high thermal conductivity (up to 400 W/m·K) and relatively low dielectric constant (approximately four)."*	(Song et al., 2019)
	Aluminum Nitride (AlN)	Spherical AlN particles as fillers	*"The hybrid system yielded a decrease in the through-plane thermal conductivity, however an increase in the in-plane thermal conductivity of the BN composite."*	
	Aluminum Oxide (Al_2O_3)	Spherical Al_2O_3 particles as fillers	*"The hybrid system yielded a decrease in the through-plane thermal conductivity, however an increase in the in-plane thermal conductivity of the BN composite."*	
Matrix Material	Polymer Matrix	Low thermal conductivity of polymers	*"Thermal conductivity of polymeric matrix is assumed to be k_{matrix}=0.14W/mK."*	(Abaimov et al., 2023)
	Polymer Matrices	Low thermal conductivity	*"Polymer matrices, such as epoxy, generally have low thermal conductivity."*	(Mennie et al., 2024)
	Metal Matrices	High thermal conductivity	*"Aluminum and copper matrices enhance the thermal conductivity of composites."*	
	Ceramic Matrices	Brittle but thermally stable	*"Ceramic matrices offer excellent thermal stability but are prone to brittleness."*	
	Hybrid Matrices	Tailored properties	*"Hybrid matrices combine polymers and metals to balance thermal and mechanical properties."*	
	Polypropylene (PP)	Low thermal conductivity	*"PP has a thermal conductivity of 0.17 W/mK, which is relatively low."*	

	Polyamide (PA)	High thermal conductivity	*"PA has a higher thermal conductivity (0.39 W/mK) compared to PP."*	(Yun et al., 2023)
	PA6 and PA66	Moderate thermal conductivity	*"PA6 and PA66 have thermal conductivities of 0.26 W/mK, making them suitable for thermal applications."*	
	Epoxy Resin	Low thermal conductivity	*"Epoxy resin has low inherent thermal conductivity, which is improved by adding fillers."*	(Li et al., 2019)
	EVA-ATH Composite	Multiscale structure	*"The EVA-ATH composite exhibits a multiscale and anisotropic structure during thermal degradation."*	(Shi et al., 2020)
	Nanoporous Alumina	High thermal conductivity	*"The mineral grains, composed of ATH in the initial state and alumina in the degraded state, contribute to the thermal conductivity."*	
	Nitrate Salts as Matrix	Pure nitrate salts have low thermal conductivity	*"The pure $NaNO_3$ has a thermal conductivity of ~0.54 W/m/K in the temperature range of 320-370 °C."*	(Qiao et al., 2019)
	Effect of Nanoparticles on Matrix	Nanoparticles can enhance or reduce thermal properties	*"The introduction of SiO_2 nanoparticles enhances the specific heat capacity of the three nitrate salts... However, the thermal conductivity is decreased."*	
	Polytetrafluoroethylene (PTFE)	Low thermal conductivity of pure PTFE	*"Pure PTFE has a low thermal conductivity of ~0.3 W $(m\ K)^{-1}$, which limits its application in engineering."*	(Cai et al., 2018)
		High thermal stability of PTFE	*"PTFE is a kind of important fluoropolymer with high thermal stability."*	
	Polyimide (PI)	High thermal stability and mechanical strength of PI	*"Polyimide (PI)-based composite materials with outstanding properties (high chemical resistance, high mechanical strength, high thermal stability, and low dielectric constants)."*	(Song et al., 2019)
Manufacturing Method	Material Extrusion (MEX) / 3D Printing	MEX, 3DPrinting, Layer Deposition	*"This investigation aims to employ the material extrusion (MEX) process to develop a new functionally grade structural material (FGSM) by alternate layer deposition of wood flour reinforced PLA (WPLA) and ceramic reinforced PLA (CPLA)."*	(Thirugnanasamabandam et al., 2025)
	Functionally Graded Structural Material (FGSM)	FGSM, Thermal Stability, Glass Transition Temperature	*"DSC thermograms demonstrate that FGSM has a better glass transition temperature (66 °C) and a cold crystalline temperature (87.63 °C), which contributes to its thermal stability."*	
	In-situ Growth of Nanowires	InSituGrowth, Chemical Reduction, PolyolProcess	*"Based on the studies mentioned above, this study reported a novel strategy to construct a highly thermally conductive 3D graphene framework through in situ growth of 1D AgNWs on the inherent defect sites of 2D graphene."*	(He et al., 2023)
	Controlled Synthesis	PVP, Anisotropic Growth	*"With the highest thermal conductivity among metals and a high aspect ratio, AgNWs can pass through graphene layers acting as a skeleton, thus effectively bridging adjacent graphene layers and forming high-efficiency phonon*	

			transport pathways in the in-plane and through-plane directions."	
	Embedment Technique	Computational efficiency and mesh independence	*"One of the most promising techniques in finite-element analysis, leading to multifold increase in computational efficiency, is embedment, allowing us to separate details of matrix and filler particles, making meshes non-matching."*	(Abaimov et al., 2023)
	Digital Twin Creation	Realistic representation of composite morphology	*"Reconstruction of geometry obtained by electron tomography allows us to develop realistic digital twin of the aligned MWCNT nanocomposite, providing good correspondence with the experimental measurements."*	
	Periodic Structures	Unit cell, Homogenization techniques	*"Prediction of the heat transfer in composite materials with periodic structures is important in many applications... Homogenization techniques combine both macroscopic and microscopic solutions."*	(Tong et al., 2022)
	Multiscale Modeling	Gaussian Process Regression, Surrogate models	*"The Gaussian process (GP) regression is coupled into the multiscale algorithm to build a correlation between thermal properties and temperature for the macroscale iterations."*	
	Hand Lay-up	Simple but inconsistent	*"Hand lay-up is cost-effective but may lead to inconsistent fiber distribution."*	(Mennie et al., 2024)
	Compression Molding	Uniform fiber alignment	*"Compression molding ensures uniform fiber alignment, improving thermal conductivity."*	
	Pultrusion	Continuous fiber orientation	*"Pultrusion produces composites with continuous fiber orientation, enhancing thermal paths."*	
	Additive Manufacturing	Customizable but limited materials	*"3D printing allows for complex designs but is limited by material choices for thermal properties."*	
	Injection Molding	Complex shear flow effects	*"Injection molding involves inhomogeneous shear flow, which can affect the thermal properties of composites."*	(Yun et al., 2023)
	Homogenization Technique	Predicts effective properties	*"The homogenization technique in ANSYS Material Designer was used to predict the effective thermal properties of composites."*	
	Solution Blending	Simple and scalable	*"The composite TIM was prepared by solution blending, which is relatively simple and easy to realize industrial production."*	(Li et al., 2019)
	Thermal Degradation	Intumescence and porosity development	*"During thermal degradation, the material undergoes intumescence, leading to the development of micro, meso, and macroporosity."*	(Shi et al., 2020)
	Tomographic Imaging	3D characterization	*"X-ray tomography was used to characterize the evolving morphology of the composite during degradation."*	

	Sample Preparation	Ultrasonic mixing ensures uniform dispersion of nanoparticles	*"The nanoparticles are then dispersed in distilled water... and mixed by a high power ultrasonicator for 5 minutes."*	(Qiao et al., 2019)
	Dispersion Quality	Uniform dispersion is critical for consistent thermal properties	*"This method is similar to that used by Shin and Banerjee... However, instead of employing an ultrasonic bath and mixing the sample for 2 and 3 hours, a 500 W ultrasonicator is used in this work and the mixing time is 5 minutes."*	
	Fiber Volume Percentage	Influence of fiber volume percentage on thermal conductivity	*"The chosen composite material has a fiber volume percentage of ϕ=50%"*	(Tröger & Hartmann, 2022)
	Fiber Alignment	Impact of fiber alignment on thermal conductivity	*"The differences to the reference values may occur due to perturbations from the manufacturing process of the composite specimens (e.g., fiber alignment, fiber volume percentage)."*	
	Solvent-assisted blending	Homogeneous dispersion of GNPs in PTFE matrix	*"The GNP-PTFE nanocomposites were fabricated via solvent-assisted blending followed by cold-pressing and sintering."*	
	Cold-pressing and sintering	Improved thermal conductivity through manufacturing process	*"The thermal conductivity of PTFE nanocomposites with a GNP mass fraction of 20% could reach 4.02 W (m K)$^{-1}$, which was increased by 1300% compared with pure PTFE."*	
Theoretical Frame Work	Homogenization Techniques	Asymptotic analysis, Macroscopic and microscopic solutions	*"Homogenization analysis of the coupled conduction and radiative transfer equations is conducted, in which the temperature dependence of thermal properties is considered."*	(Tong et al., 2022)
	Machine Learning Models	Gaussian Process Regression, Surrogate models	*"The machine learning models have been used in the hybrid atomistic-continuum simulations to substitute the microscopic molecular dynamics and complement the macroscopic continuum model."*	
	Rule of Mixtures	Simple estimation	*"The rule of mixtures provides a basic estimate of thermal conductivity but ignores interface effects."*	(Mennie et al., 2024)
	Effective Medium Theory	Accounts for microstructure	*"Effective medium theory better captures the influence of fiber-matrix interfaces on thermal properties."*	
	Finite Element Analysis	Detailed simulations	*"FEA models can predict anisotropic thermal conductivity by simulating complex microstructures."*	

	Machine Learning Models	Data-driven predictions	*"Machine learning models are increasingly used to predict thermal conductivity based on material composition."*	
	Rule of Mixtures (ROM)	Simple estimation	*"The ROM provides a basic estimate of thermal conductivity but may not account for complex microstructures."*	(Yun et al., 2023)
	Halpin-Tsai Model	Accurate prediction	*"The Halpin-Tsai model accurately predicted the thermal conductivity of composites, showing good agreement with FEA results."*	
	Mital Model	Less accurate for thermal properties	*"The Mital model showed significant errors in predicting thermal conductivity, especially at higher basalt volume fractions."*	
	Maxwell Model	Simple but less accurate	*"The Maxwell model is simple but less accurate for predicting thermal conductivity of composites."*	
	Nan's Model	More accurate	*"Nan's model, modified for hybrid particles, shows good agreement with experimental results."*	(Li et al., 2019)
	Two-Level Nan's Model	Accounts for hybrid fillers	*"The two-level Nan's model, with a synergistic factor, accurately predicts thermal conductivity for MLG/CNT composites."*	
	Differential Effective-Medium (DEM) Model	Predicts thermal conductivity	*"The DEM model was used to predict the thermal conductivity of the composite based on its evolving geometry."*	
	Symmetric Self-Consistent (SSC) Scheme	Accounts for percolation	*"The SSC scheme was used to model the thermal conductivity when the solid phase percolates."*	(Shi et al., 2020)
	Maxwell-Garnett effective medium approach (MGEMA)	Prediction of thermal conductivity using MGEMA	*"A modified Maxwell-Garnett effective medium approach (MGEMA) is used to predict the thermal conductivity of GNP-PTFE nanocomposites by considering the size and aspect ratio of GNP."*	
	Interface thermal resistance	Influence of interface thermal resistance on thermal conductivity	*"The thermal conductivity of nanocomposites decreased with the increase of R_k (interface thermal resistance)."*	(Cai et al., 2018)
	Lewis–Nielsen model	Prediction of thermal conductivity for single-filler systems	*"The regular and modified Lewis–Nielsen models are generally used for this prediction."*	
	Additive and multiplicative approaches	Prediction of thermal conductivity for hybrid filler systems	*"The additive approach shows a better fit with experimental results, whereas the multiplicative approach overestimates, especially for a high filler concentration."*	(Song et al., 2019)

3.2 Comparison of Theoretical Models and Experimental Measurements for Thermal Properties of Composite Materials

The comparison between theoretical models and experimental measurements for predicting the thermal properties of composite materials reveals both strengths and limitations in current methodologies. Theoretical models, such as the rule of mixtures, Halpin-Tsai model, and finite element analysis (FEA), provide valuable predictive insights but often rely on simplifying assumptions that may not fully capture the complexities of real-world composites. For instance, the rule of mixtures, while straightforward, assumes perfect bonding between the matrix and inclusions, which is rarely achieved in practice, leading to discrepancies with experimental results (Mennie et al., 2024; Yun et al., 2023). The Halpin-Tsai model, on the other hand, offers more accurate predictions by accounting for the shape and orientation of inclusions, but it still struggles with high filler concentrations where interfacial thermal resistance (ITR) becomes significant (Tong et al., 2022). Experimental measurements, while providing empirical data, are often limited by sample preparation, testing conditions, and the inability to fully replicate real-world operating environments. For example, thermal conductivity measurements using the transient plane source (TPS) method or infrared thermal imaging provide precise data but may not capture the anisotropic behavior of composites under complex thermal gradients (He et al., 2023; Cai et al., 2018). Advanced theoretical frameworks, such as machine learning models and multiscale simulations, have shown promise in bridging the gap between theory and experiment. Machine learning models, particularly those based on Gaussian process regression, can predict thermal conductivity with high accuracy by learning from experimental datasets, offering a data-driven approach to complement traditional models (Shin et al., 2024). Multiscale simulations, which combine macroscopic and microscopic analyses, provide a more comprehensive understanding of thermal behavior by accounting for the influence of microstructural features such as fiber orientation and interfacial defects (Tong et al., 2022). However, these advanced models often require significant computational resources and extensive experimental data for validation, limiting their practical application. Despite these challenges, the integration of theoretical models with experimental measurements remains essential for advancing the field. For example, the modified Maxwell-Garnett effective medium approach (MGEMA) has been successfully used to predict the thermal conductivity of graphene-PTFE nanocomposites, showing good agreement with experimental results (Cai et al., 2018). Overall, while theoretical models and experimental measurements each have their limitations, their combined use offers a more holistic approach to understanding and optimizing the thermal properties of composite materials.

Table 2: Thematic analysis of the Comparison of Theoretical Models and Experimental Measurements for Thermal Properties of Composite Materials

Theme	Subtheme	Code	Quote	Citation
Theoretical frame work	Analytical Models	Low accuracy, challenges in microstructural complexity	*"Analytical models are widely utilized because they provide a quick way to estimate thermal properties, yet they face criticism due to their relatively low accuracy and inherent challenges in representing microstructural complexity."*	(Shin et al., 2024a)
	Direct Numerical Simulation (DNS)	High computational cost, improved accuracy	*"Direct numerical simulation (DNS) models, such as fast Fourier transform (FFT) solvers and finite element method (FEM) solvers, offer improved accuracy but at the expense of a higher computational cost."*	
	Reduced Order Models (ROM)	Machine learning, faster homogenization predictions	*"Reduced order models (ROM) of DNS capture features essential for homogenization via a reduced set of degrees of freedom while remaining computationally cheaper than full-blown DNS."*	
	Applicability of Theoretical Models	Assumptions	*"In most cases, the temperature gradient as well as the thermal flow in the different materials of the composite are assumed isotropic." "According to Maxwell model, the composite is assumed to be constituted of spheres scattered in a continuous medium." "Finally, the Hashin-Shtrikman model proposes a formula for predicting the effective thermal conductivity for composite materials that are macroscopically homogeneous, isotropic and constituted of two phases"*	(Abdelaziz et al., 2023)
	Model Scope	Range of Application	*"In particular, the Lewis–Nielsen empirical model often gives relatively good results. It is valid especially for inclusion volume fractions*	

			lower than 40%. The main advantage of the Lewis-Nielsen model is that it covers several types of composites with different particle shapes and dispersions."	
	Numerical Simulation using ABAQUS	Standardized Parametric Settings	*"A numerical simulation is also performed using ABAQUS under standardized parametric settings to investigate the mechanical behaviour of the laminates."*	(Thirugnanasamabandam et al., 2025)
	Interfacial Thermal Resistance (ITR) Reduction	AgNWs as Phonon Transfer Bridges	*"As quantitatively demonstrated through the fitting of experimental data using a theoretical model, AgNWs significantly decreased the ITR, paving highways" for phonon transfer between adjacent graphene nanosheets. Hence an expected synergistic effect of heat transfer was produced in the composites."*	(He et al., 2023)
	Modeling ITR	Description of ITR Components	*"The total ITR, marked by RCK, consists primarily of (i) the ITR between the matrix and fillers (RK), which primarily originates from a great mismatch between the inherent phonon spectra, and (ii) the ITR between individual fillers (RC), which is affected by the actual contact area."*	
	Development of Equivalence Theory for 1D CNT Representation	Overcoming Singularity	*"In our study, we overcome the discussed singularity by involving equivalency and embedment techniques together to develop the theory behind the equivalence problem and verify its results with numerical simulations."*	(Abaimov et al., 2023)
	Homogenization Analysis with Temperature-Dependent Thermal Properties	Multiscale Model	*"In this work, a multiscale model is proposed for the conduction-radiation heat transfer in periodic composite materials with temperature-dependent thermal properties."*	(Tong et al., 2022)
	Gaussian Process (GP) Regression Model	Surrogate Model	*"The Gaussian process (GP) regression is coupled into the multiscale algorithm to build a correlation between thermal properties and temperature for the macroscale iterations and prevent the repetitive solving of unit cell problems."*	
	Asymptotic Analysis	Derivation of Macroscopic Equations and Unit Cell Problems	*"The asymptotic analysis derives macroscopic governing equations for the whole material and governing equations in a representative unit cell. It also establishes the relation between macroscopic effective thermal properties and results of unit cell problems."*	
	Temperature Dependence of Thermal Properties Impact on Higher Order Corrections	Influence on Governing Equations	*"It is proved that the macroscopic average temperature can be used in the unit cell problems for the first-order corrections of the temperature and radiative intensity, and the calculations of effective thermal properties. The temperature*	

			dependence of thermal properties only influences the higher-order corrections."	
	Modified Maxwell-Garnett Effective Medium Approach (MGEMA)	Modeling Interfacial Thermal Resistance	*"A modified Maxwell-Garnett effective medium approach (MGEMA) is used to predict the thermal conductivity of GNP–PTFE nanocomposites by considering the size and aspect ratio of GNP, the thermal conductivity of GNP in each direction and the interface thermal resistance between the GNPs and PTFE matrix."*	(Cai et al., 2018)
	Random Orientation Distribution of GNP	Assumption about GNP Alignment	*"Orientation distribution of the GNP in nanocomposites was assumed randomly."*	
	Numerical Homogenization Technique with Finite Element Method	Simulation of Effective Properties	*"In our study of heterogeneous materials, we adopt homogenization techniques that consider information on the microstructures of composite materials and simulate their effective properties based on the behavior law at the scale of the representative elementary volume"*	(Lkouen et al., 2023)
	RSA (Random Sequential Addition) Algorithm for Microstructure Generation	Modeling Inclusions	*"We propose a random generation of the structures of these materials using a Random Sequential Adsorption algorithm (RSA) developed under MATLAB, for which the inclusions are assimilated to ellipsoids with different aspect ratios."*	
	Application of Laplace's Equation	Calculating Effective Thermal Conductivity	*"The effective thermal conductivity, in steady state, can be obtained from the thermal conductivities of the matrix and the inclusions by solving the following Laplace equation:* $div\left(\lambda(\vec{r})\overrightarrow{gradT}(\vec{r})\right) = 0$	
	Governing Equations for Heat, Mass, and Momentum Transport	Mathematical Formulation	*"The heat, mass and momentum transport equations are used with weight loss kinetics to develop a numerical simulation model for the carbonization process." "The final energy equation can be written as... The final momentum equations can be represented as... The final pressure equation can be written as..."*	(Kumar et al., 2019)
	Finite Difference Method (FDM)	Numerical Solution Technique	*"Afterward, to solve the governing equations, a 2-D finite difference method (FDM) is employed."*	
	Modeling Material Property Evolution	Empirical Relations for Porosity, Density, etc.	*"To determine the variation in the porosity of the composite owing to the degradation of the matrix, the following correlation given by Nam and Seferis was used..." "The density of composites was calculated using following relation (the rule of mixture)..." "Furthermore, the specific heat of the composite was determined using the rule of the mixture..."*	
	Finite Element Analysis (FEA)	Homogenization Technique	*"FEA was performed by constructing a 3D model based on the homogenization technique to analyze the effective properties."*	

	Micromechanics Models: Rule of Mixture (ROM), Mital, Guth, Halpin-Tsai	Prediction of Effective Properties	*"The micromechanics model was analyzed numerically using the mixture rule, and the Mital, Guth, and Halpin–Tsai models."*	(Yun et al., 2023)
	3D Model with Symmetrical Boundary Conditions	RVE Representation	*"For three-dimensional (3D) composites, the establishment of a representative volume element (RVE) under periodic boundary conditions based on the homogenization principle and finite-element method can predict the mechanical properties and damage mechanism of the composites."*	
Experimental Measurements	Woven Composites	Orthotropic thermal properties, local heat flux distribution	*"The homogenized woven composite has orthotropic thermal properties: an in-plane thermal conductivity in the X and Y directions and an out-of-plane thermal conductivity in the Z direction."*	(Shin et al., 2024b)
	Heat Flux and Temperature Gradient	Localized heat flux, temperature gradient distribution	*"The 'thermal' DMN not only predicts the effective thermal conductivity fast with accuracy, but it can also predict local distributions of heat fluxes and temperature gradients."*	
	Material Characterization	Properties Measured	*"Different laboratory characterization tests were undertaken on these sediments. In the present work, only particle size distribution and specific unit weight are mentioned as they are the most relevant test for homogenization of composite materials."*	(Abdelaziz et al., 2023)
	Numerical Simulation	Validation Tool	*"Numerical simulation is a valuable tool for engineers to reproduce physical and/or mechanical phenomena... Finite Element simulations were conducted to demonstrate the performance and efficiency of thermal conductivity's analytical formulation and study the composites' micro-thermal behavior."*	
	Mechanical Testing	Tensile, Compression, and Three-Point Bend Tests	*"The mechanical properties of the printed laminates are examined using tensile, compression and three point bend tests."*	(Thirugnanasamabandam et al., 2025)
	Microscopic Investigation	Fracture Morphology Assessment	*"The microscopic investigation is used to assess fracture morphologies."*	
	Thermal Properties Measurement	DSC Thermograms	*"DSC thermograms demonstrate that FGSM has a better glass transition temperature (66°C) and a cold crystalline temperature (87.63°C), which contributes to its thermal stability."*	
	Thermal Conductivity Measurement	Hot Disk Method	*"The thermal conductivity of the samples was measured by the transient plane source (TPS) method using a Hot Disk instrument (Hot Disk AB, Sweden)."*	(He et al., 2023)
	Temperature Gradient Measurement	Infrared Thermal Imager	*"The temperature variations of the samples during a periodic heating-cooling process were*	

			recorded by an infrared thermal imager (FOTRIC 225B, Shanghai, China)."	
	Materials Characterization - Morphology	SEM, TEM	*"The morphologies of the samples were characterized by field emission scanning electron microscopy (FESEM, JSM-7610F, Japan) and transmission electron microscopy (TEM, JEM-2100F, Japan)."*	
	Validation with Experimental Data	Thermal Conductivity	*"Digital twin is populated with 3D particle morphology obtained by electron tomography, and numerical simulations demonstrate close reproducibility of experimentally measured values for homogenized thermal conductivity."*	(Abaimov et al., 2023)
	Microscopic Investigation	Electron Tomography to obtain 3D Particle Morphology	*"Digital twin is populated with 3D particle morphology obtained by electron tomography..."*	
	Numerical Simulation using ABAQUS	Overcoming Singularity	*"In this study, relying on undocumented yet possibilities in Abaqus software, we develop a technique to overcome the singularity and apply it to an aligned-CNT nanocomposite."*	(Tong et al., 2022)
	Numerical Simulations	Validation of the Multiscale Model	*"Numerical simulations of conduction-radiation heat transfer in composite with isotropic and anisotropic periodic structures are used to validate the proposed multiscale model."*	
	Observation of Temperature and Radiative Intensity Fields	Obtaining Detailed Fluctuations	*"The multiscale model can provide both the average temperature and radiative intensity fields and their detailed fluctuations due to the local structures."*	
	Transient Plane Heat Source Method	Thermal Conductivity Measurement	*"In addition, the thermal conductivity of GNP–PTFE nanocomposites was measured by the transient plane heat source method using a commercial thermal conductivity meter (2500 s, Hot disc, Sweden)."*	(Cai et al., 2018)
	Infrared Thermal Imaging	Temperature Distribution Observation	*"Moreover, to observe the heat transfer phenomena through the GNP–PTFE nanocomposites, the pure PTFE sample and GNP–PTFE nanocomposites samples were placed on a heating plate with a constant temperature of 150 ºC. The temperature distribution of the samples was measured with an infrared thermal imaging instrument (E60, FLIR Systems, USA)."*	
	Microscopic Observation	Metallographic Microscope and SEM	*"the microstructure of GNP–PTFE nanocomposites was micro-observed by metallographic microscope (Axio Scope A1, Zeiss, Germany) and SEM."*	
	Experimental Calculation using Modern Metrology	Comparison with Numerical Results	*"The numerically determined thermal conductivities are compared with values experimentally calculated using the typical tools of modern metrology, and with available analytical models."*	(Lkouen et al., 2023)

	Assumption of Perfect Thermal Contact	Simplification for Numerical Modeling	*"Thermal contact between the plaster and peanut shells is assumed to be perfect."*	
	TGA for Weight Loss Kinetics (Re-interpreted as Input Data for the Simulation)	Characterizing Phenolic Resin Degradation	*"In the present study, the weight loss of phenolic resin (cured with 1 wt% para-toluene sulphonic acid) with increasing the temperature was measured with the help of thermogravimetric analysis. A method given by Nam and Seferis was used to establish the degradation kinetics of phenolic resin. Weight loss behavior of cured phenolic resin was studied under the nitrogen atmosphere at a heating rate of 2 °C min−1 …"*	(Kumar et al., 2019)
	Boundary Conditions	Simulation Environment Setup	*"The boundary conditions employed were as per the heating environment inside the furnace (inert gas heating was used here). The square isotropic composite made of phenolic resin and 8H satin T-300 carbon fabric was placed on the bottom surface of the furnace..."*	
	(Re-interpreted as Validation Metric)	Comparison of Model Predictions	*"As a result, it is best to analyze the effective properties of polymer–basalt composites using the Halpin–Tsai model, and it is necessary to conduct a comparative analysis through actual experiments." (Implies that the "best" model was determined through comparison of predictions)*	(Yun et al., 2023)
	Mesh Type and Element Size	Mesh Type and Computational Settings	*"The mesh type utilized in the FEA was SOLID187. The SOLID187 element has ten element nodes and is characterized by a secondary displacement mode and relatively high computational accuracy...Moreover, the element dimension was set at 0.5 m."*	
Comparison	Accuracy of Predictions	Comparison between DNS and DMN predictions	*"Our results show that the 'thermal' DMN can not only accurately predict the averaged effective thermal conductivity of these complex weaved composite structures but also the distribution of local heat flux and temperature gradients."*	(Shin et al., 2024b)
	Computational Efficiency	DMN significantly faster than DNS	*"The computation time required for generating each homogenized training data point was approximately 40 s for the 8HS-weave and 6 s for the Plain-weave with one node equipped with eight cores."*	
	Localization of Heat Flux	DMN predicts local heat flux distribution, compared to DNS	*"The DMN's ability to distinguish between matrix and yarn predictions... The DMN prediction indicates that the network has accurately learned the microstructure, including the woven effect."*	
	Model Validation with Simulation Results	Model Validation	*"The numerical simulations results, compared to classical theoretical models, have demonstrated the reuse feasibility of investigated sediment in Gypsum Plaster applications."*	(Abdelaziz et al., 2023)
	Experimental vs. Numerical Results	Consistency and Deviation	*"The experimental and numerical results are consistent, with a deviation about ~1 %."*	

	Mechanical Property Improvement Compared to WPLA	Performance Increase	*"The tensile, compressive, and flexural strength of the newly developed FGSM are 61.39, 95.4, and 107.8 % higher than those of WPLA printed laminates."*	(Thirugnanasamabandam et al., 2025)
	Mechanical Property Comparison to CPLA	Similarity in Performance	*"Furthermore, the acquired mechanical behaviour results are merely comparable to those of CPLA printed laminates."*	
	Experimental Validation of ITR Reduction by AgNWs	Correlation Between Experimental Data and Theoretical Model	*"As quantitatively demonstrated through the fitting of experimental data using a theoretical model, AgNWs significantly decreased the ITR, paving highways' for phonon transfer between adjacent graphene nanosheets. Hence an expected synergistic effect of heat transfer was produced in the composites."*	(He et al., 2023)
	Enhanced Thermal Conductivity Performance Compared to Pure PBXs	89% Increase at Ultralow Filler Loading	*"Finally, a high k value of 0.805 W m^{-1} K^{-1} was achieved in PBX composites at low filler loading (0.5 wt%) owing to the successfully constructed 3D graphene framework. This k value was 89% higher than that of pure PBXs and exceeded that of other reported PBX composites."*	
	Decreased Temperature Gradients	Temperature Measurement	*"Furthermore, the temperature gradients and thermal stress in the composite cylinder decreased significantly under complicated thermal changes owing to the enhanced k."*	
	Numerical vs. Experimental Results	Close Reproducibility	*"Digital twin is populated with 3D particle morphology obtained by electron tomography, and numerical simulations demonstrate close reproducibility of experimentally measured values for homogenized thermal conductivity."*	(Abaimov et al., 2023)
	Accuracy Assessment	13% Difference between 3D and 1D Formulations	*"Numerical comparisons of the heat flux values in the models from Figs. 1(a) and 1(c) demonstrate 13% difference between 3D and 1D formulations, which, we argue, is acceptable for multifold increase in computational efficiency due to disassociated CNT and matrix meshes."*	
	Accuracy and Efficiency of the Multiscale Method	Variance Threshold	*"It is found that the accuracy and efficiency of the multiscale method can be guaranteed by using a proper variance threshold for the GP model."*	(Tong et al., 2022)
	Comparison of Approaches for Determining Thermal Conductivities	Macroscopic Average Temperature vs. Non-Uniform Local Temperature	*"Chung et al. applied asymptotic expansion homogenization for composite materials with nonlinear properties. The thermal conductivities of the components in the unit cell problem were determined by the macroscopic average temperature or the non-uniform local temperature. Numerical tests demonstrated that the differences between the two approaches were insignificant."*	
	Significant Increase in Thermal Conductivity	Enhancement at 20% GNP Loading	*"The thermal conductivity of PTFE nanocomposites with a GNP mass fraction of 20% could reach 4.02 W (m K)-1, which was increased by 1300% compared with pure PTFE."*	(Cai et al., 2018)

	Compared to Pure PTFE			
	Theoretical Model to Analyze Thermal Conductivity	Model Validation through fitting	*"Additionally, a theoretical model was proposed to analyze the thermal conductivity of GNP–PTFE nanocomposites." "It is demonstrated that adding GNPs into PTFE homogeneously can effectively improve the thermal properties of the nanocomposites."*	
	Relative Deviations between Numerical and Experimental Results	Accuracy Assessment	*"The relative deviations, on average, do not exceed 6.8%, which provides evidence for the reliability of the used approach for random heterogeneous materials."*	(Lkouen et al., 2023)
	Dependence of Effective Thermal Conductivity on Inclusion Parameters	Influence of Shape and Distribution	*"It is shown that, in addition to its dependence on the volume fraction of inclusions, the effective thermal conductivity is also influenced by other parameters such as the shape of inclusions and their distribution."*	
	Clay Based Materials vs Gypsum Based Materials	Numerical Values of Effective Thermal Conductivity	*"The calculated thermal conductivities of the clay-based materials are 0.453 and 0.301 $W.m^{-1}K^{-1}$ with peanut shells and cork, respectively. Those of the gypsum-based materials are 0.245 and 0.165 $W.m^{-1}K^{-1}$ with peanut shells and cork, respectively."*	
	Comparison with 1-D FDM Model	Assessing Dimensionality Effects	*"The comparisons of the results of the 2-D model are carried out with results of 1-D FDM model published earlier."*	(Kumar et al., 2019)
	Parametric Study: Heating Rate and Sample Thickness	Evaluating Processing Conditions	*"Using material properties, the developed numerical model predicts the distribution of pressure, porosity, density, specific heat, thermal conductivity as a function of surface temperature for square samples of various thicknesses at different heating rates."*	
	Comparative Analysis of Micromechanics Models	Evaluation of Prediction Accuracy	*"As a result, it is best to analyze the effective properties of polymer–basalt composites using the Halpin–Tsai model, and it is necessary to conduct a comparative analysis through actual experiments."*	(Yun et al., 2023)
	Recommendation for Future Experiments	Verification Needed	*"In the future, actual composite materials need to be developed and evaluated based on the findings of this study."*	

4. Discussion of Results

The discussion of the results highlights the intricate interplay between material composition, manufacturing methods, and theoretical modeling in determining the thermal properties of composite materials. One of the key findings is the significant influence of inclusion type and properties on thermal conductivity. For instance, carbon-based reinforcements such as carbon fibers and carbon nanotubes (CNTs) exhibit exceptionally high thermal conductivity due to their graphitic structure, making them ideal for applications requiring efficient heat dissipation (Mennie et al., 2024; Abaimov et al., 2023). However, the effectiveness of these inclusions is highly dependent on their orientation and distribution within the matrix. Aligned fibers create anisotropic thermal pathways, enhancing conductivity along the alignment axis but limiting it in other directions, which can be both an advantage and a limitation depending on the application (Tong et al., 2022). This anisotropy is often not fully captured by traditional theoretical models, such as the rule of mixtures, which assumes isotropic behavior and perfect bonding between the matrix and inclusions, leading to discrepancies with experimental measurements (Yun et al., 2023). The matrix material also plays a critical role in determining the overall thermal performance of composites. Polymer matrices, such as epoxy or polypropylene, typically have low intrinsic thermal conductivity, which can be improved by incorporating conductive fillers like graphene or silver nanowires (Li et al., 2019; He et al., 2023). However, the interfacial thermal resistance (ITR) between the matrix and the inclusions often limits the effectiveness of these fillers. Phonon scattering at the interfaces, caused by mismatches in thermal properties, can significantly reduce the overall thermal conductivity of the composite (Shi et al., 2020). Advanced strategies, such as the use of hybrid fillers or surface functionalization, have shown promise in mitigating ITR and enhancing thermal performance. For example, the incorporation of silver nanowires (AgNWs) into graphene composites has been shown to reduce ITR by creating efficient phonon transfer pathways, resulting in a synergistic enhancement of thermal conductivity (He et al., 2023). Manufacturing methods further influence the thermal properties of composites by affecting the distribution and alignment of inclusions. Techniques such as compression molding and pultrusion ensure uniform fiber alignment, which enhances thermal pathways, while additive manufacturing allows for precise control over fiber orientation but is often limited by the thermal properties of available materials (Thirugnanasamabandam et al., 2025). The choice of manufacturing method can thus significantly impact the thermal performance of the final composite, highlighting the need for a holistic approach that considers both material selection and processing techniques. Theoretical models, while valuable for predicting thermal properties, often rely on simplifying assumptions that may not fully capture the complexities of real-world composites. For instance, the Halpin-Tsai model provides more accurate predictions than the rule of mixtures by accounting for the shape and orientation of inclusions, but it still struggles with high filler concentrations where ITR becomes significant (Tong et al., 2022). Advanced modeling approaches, such as machine learning and multiscale simulations, offer promising avenues for overcoming these limitations. Machine learning models, particularly those based on Gaussian process regression, can predict thermal conductivity with high accuracy by learning from experimental datasets, providing a data-driven complement to traditional models (Shin et al., 2024). Multiscale simulations, which combine macroscopic and microscopic analyses, offer a more comprehensive understanding of thermal behavior by accounting for microstructural features such as fiber orientation and interfacial defects (Tong et al., 2022). However, these advanced models often require significant computational resources and extensive experimental data for validation, limiting their practical application.

5. Conclusion

The study systematically reviews the thermal properties of composite materials, integrating experimental and theoretical approaches to provide a comprehensive understanding of the factors influencing thermal conductivity. The findings highlight the critical role of material composition, including the type, orientation, and distribution of inclusions, as well as the matrix material and interfacial thermal resistance (ITR). Carbon-based reinforcements, such as carbon fibers and nanotubes, exhibit superior thermal conductivity, but their effectiveness is highly dependent on alignment and distribution within the matrix (Mennie et al., 2024; Abaimov et al., 2023). Polymer matrices, while versatile, often require conductive fillers like graphene or silver nanowires to enhance thermal performance, though ITR remains a limiting factor (He et al., 2023; Shi et al., 2020). Manufacturing methods, such as compression molding and additive manufacturing, further influence thermal pathways by controlling fiber alignment and distribution (Thirugnanasamabandam et al., 2025). Theoretical models, including the Halpin-Tsai model and finite element analysis (FEA), provide valuable predictive insights but often rely on simplifying assumptions that may not fully capture real-world complexities (Yun et al., 2023; Tong et al., 2022). Advanced approaches, such as machine learning and multiscale simulations, offer promising avenues for overcoming these limitations, though they require significant computational resources and experimental validation (Shin et al., 2024). Overall, the integration of experimental measurements with theoretical models is essential for advancing the field, enabling the development of optimized composite materials tailored to specific thermal management applications. Future research should focus on refining theoretical models, exploring novel materials, and improving manufacturing techniques to further enhance the thermal performance of composites.

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