

Optimization of Thermal Conductivity in Sustainable AlN–Fly Ash Based Composite Materials

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ABSTRACT

This paper investigates the optimization of thermal conductivity in sustainable aluminum nitride (AlN)–fly ash based composite materials aimed at eco-friendly thermal management applications. Fly ash, an industrial waste by-product, is incorporated to enhance sustainability and reduce material cost, while AlN is used to improve heat conduction due to its high intrinsic thermal conductivity. Composite samples were fabricated with varying AlN and fly ash compositions, and their thermal conductivity was experimentally evaluated using standard measurement techniques. The influence of material composition and microstructural characteristics, including particle dispersion, interfacial bonding, and porosity, on thermal performance was systematically analyzed. An optimization strategy was employed to determine the optimal reinforcement ratio that achieves a balance between enhanced thermal conductivity and environmental sustainability. The results indicate that increasing AlN content significantly improves thermal conductivity, while the presence of fly ash maintains eco-efficiency with acceptable performance trade-offs. The optimized composite demonstrates superior thermal behavior compared to conventional sustainable composites, highlighting its potential for applications in electronics cooling, energy systems, and environmentally conscious construction materials.

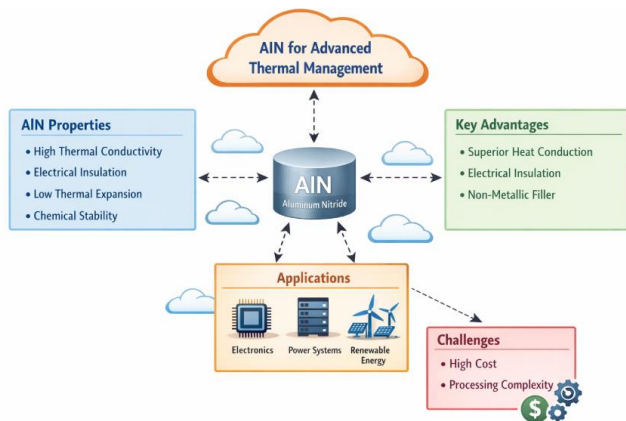
Keywords—Aluminum nitride (AlN), Fly ash, Eco-thermal composites, Thermal conductivity optimization, Sustainable materials, Thermal management.

INTRODUCTION

The rapid advancement of modern engineering systems, particularly in electronics, energy devices, and construction technologies, has intensified the demand for materials with efficient thermal management capabilities. Effective dissipation and regulation of heat are critical for ensuring system reliability, operational efficiency, and long-term durability. Conventional thermal materials, although capable of providing high thermal conductivity, are often associated with high production costs, intensive energy consumption, and adverse environmental impacts. Consequently, the development of sustainable and eco-friendly thermal composite materials has emerged as a significant research focus in materials science and thermal engineering. In recent years, composite materials have gained considerable attention due to their ability to combine the advantageous properties of multiple constituents, enabling tailored performance for specific applications. By carefully selecting and optimizing the matrix and reinforcement phases, composites can be engineered to achieve desirable thermal, mechanical, and environmental characteristics. Among these properties, thermal conductivity plays a pivotal role in applications such as electronic packaging, heat sinks, thermal interface materials, energy storage systems, and sustainable building components. However, enhancing thermal conductivity in composite systems while maintaining environmental sustainability remains a challenging task. Industrial waste utilization has been recognized as a promising strategy for developing sustainable materials and addressing environmental concerns related to waste disposal. Fly ash, a by-product generated from coal-fired power plants, is produced in large quantities worldwide and poses serious ecological and health challenges if not properly managed. Due to its fine particle size, low density, chemical stability, and

pozzolanic nature, fly ash has been widely explored as a filler or reinforcement in cementitious materials, polymers, and metal matrix composites. Its incorporation into composite systems not only contributes to waste valorisation and reduced environmental footprint but also offers potential improvements in material properties such as dimensional stability and cost-effectiveness. Fly ash generally exhibits low thermal conductivity, which can limit its direct application in thermal management materials. To overcome this limitation, the incorporation of high-thermal-conductivity ceramic fillers has been extensively investigated. Aluminium nitride (AlN) is a ceramic material known for its exceptionally high thermal conductivity, electrical insulation, low thermal expansion coefficient, and excellent chemical stability. These properties make AlN an attractive candidate for advanced thermal management applications, particularly in electronic and electrical systems shown in Fig. 1. Unlike metallic fillers, AlN provides high heat conduction without compromising electrical insulation, which is a critical requirement in many modern technologies. However, the widespread use of AlN is often constrained by its high cost and processing complexity, necessitating optimized material design strategies to achieve performance enhancement with minimal material usage.

The integration of AlN with fly ash in composite materials presents a synergistic approach to achieving both high thermal performance and sustainability. While AlN contributes significantly to heat transfer efficiency, fly ash enhances eco-friendliness, reduces production costs, and supports sustainable material development through waste reutilization. The combined use of these materials enables the development of eco-thermal composites with tailored thermal conductivity suitable for a wide range of applications.



Overview of AlN Based Thermal Efficiency

Nevertheless, the overall thermal performance of such composites is strongly influenced by factors such as filler content, particle size distribution, interfacial bonding between constituents, and microstructural homogeneity. Optimization of thermal conductivity in composite materials requires a comprehensive understanding of structure–property relationships. The distribution and connectivity of high-conductivity pathways, interfacial thermal resistance, and porosity levels play a decisive role in governing heat transfer mechanisms. Improper dispersion of AlN particles or weak interfacial bonding can significantly hinder thermal conduction, even at higher filler loadings. Therefore, systematic optimization of material composition and processing parameters is essential to maximize thermal conductivity while preserving mechanical integrity and sustainability objectives. Several studies have reported the enhancement of thermal conductivity in composites using ceramic fillers such as boron nitride, silicon carbide, and aluminium oxide. However, comparatively fewer investigations have focused on AlN-based eco-thermal composites incorporating industrial waste materials such as fly ash. Moreover, limited research is available on optimizing the combined effect of AlN and fly ash to achieve controlled and application-specific thermal conductivity. This research gap highlights the need for systematic experimental studies that explore the interaction between sustainable fillers and high-performance ceramics within a unified composite framework. In this context, the present study focuses on the design, fabrication, and optimization of sustainable AlN–fly ash based composite materials with tailored thermal conductivity. By varying the weight fractions of AlN and fly ash, the influence of composition on thermal performance is experimentally evaluated. The study also examines the role of microstructural characteristics, including particle dispersion and interfacial interactions, in governing thermal behavior. An

optimization strategy is employed to identify the optimal composition that balances enhanced thermal conductivity, material sustainability, and structural stability.

LITERATURE REVIEW

The development of composite materials with improved thermal, mechanical, and environmental performance has been an active area of research for several decades. Early studies on metal matrix and hybrid composites primarily focused on enhancing wear resistance, mechanical strength, and durability through the incorporation of ceramic and waste-based reinforcements. Acharya et al. [1] investigated the erosive wear behavior of red mud-filled metal matrix composites and demonstrated that industrial waste materials can be effectively utilized to improve performance while reducing environmental impact. Their work laid an important foundation for the reuse of industrial by-products in advanced composite materials. Subsequent research expanded toward hybrid reinforcements and advanced fillers. Agarwal et al. [2] studied the fabrication and machinability of Al 7075 composites reinforced with hexagonal boron nitride and graphene, reporting notable improvements in material performance due to the synergistic effect of hybrid fillers. Similarly, Alagarsamy et al. [3] focused on machining behavior and process optimization of aluminium-based composites reinforced with ceramic particulates, emphasizing the role of reinforcement content and distribution on overall performance. These studies highlighted the importance of optimized processing parameters and filler selection in composite design. Agro-waste-derived reinforcements have also gained attention due to their sustainability advantages. Alaneme and Adewale [4] examined the influence of rice husk ash and silicon carbide ratios on the mechanical behavior of Al–Mg–Si alloy composites, demonstrating that waste-based reinforcements can effectively complement synthetic ceramics. Further investigations by Alaneme and Ajayi [5] and Alaneme and Olubambi [6] revealed that rice husk ash-based hybrid composites exhibit improved microstructural stability, wear resistance, and corrosion behavior. These findings were reinforced by additional studies on aluminium matrix hybrid composites containing alumina, rice husk ash, graphite, and bamboo leaf ash, which confirmed that hybridization improves property balance and material sustainability [7], [8]. While most early investigations focused on mechanical and tribological properties, recent research has begun addressing multifunctional performance requirements. Allison and Cole [10] discussed the potential of metal matrix composites in automotive applications, emphasizing weight reduction, thermal stability, and performance optimization. Similarly, Al-Mukhtar [11] highlighted the importance of material integrity and crack resistance in aerospace structures, indirectly underscoring the need for composites with controlled thermal and mechanical behavior. Research on erosion, corrosion, and wear behavior of hybrid composites further demonstrated the influence of reinforcement selection and microstructure. Aribio et al. [12] studied erosion–corrosion behavior in aluminium hybrid composites and reported that optimized reinforcement combinations significantly enhance durability. Comprehensive reviews by Arora and Sharma [13], [14] summarized the progress in monolithic and hybrid metal matrix composites reinforced with industrial and agro-waste materials, concluding that waste-derived reinforcements offer a viable route toward sustainable composite development while maintaining acceptable performance levels. Advancements in composite processing and microstructural control have also contributed to improved material properties. Cheneke and Karunakar [15] analysed microstructure and mechanical behavior of stir-processed aluminium composites and emphasized the role of uniform reinforcement distribution and interfacial bonding. Studies on erosion mechanisms and surface interactions, such as those by Chowdhury et al. [16] and Contreras et al. [17], provided deeper insights into particle–matrix interactions, wettability, and interfacial kinetics, which are equally relevant for thermal transport behavior. More recent investigations have explored advanced fillers such as graphene oxide and ceramic particulates to enhance multifunctional properties. Dasari et al. [19] demonstrated that graphene oxide reinforcement improves the mechanical performance of aluminium matrix composites, while David et al. [20] reported enhanced wear resistance in in-situ fabricated ceramic-reinforced aluminium alloys. Although these studies primarily focused on mechanical and tribological properties, their findings highlight the broader potential of ceramic and nano-scale fillers to influence heat transfer pathways in composites. Additionally, Alidokht et al. [21] emphasized the strong correlation between microstructure and functional performance in composite coatings, reinforcing the importance of microstructural optimization. Despite the extensive body of literature on hybrid and waste-reinforced composites, limited studies have specifically addressed the optimization of thermal conductivity in sustainable composite systems. In particular, the combined use of industrial waste materials such as fly ash with high-thermal-conductivity ceramics like aluminium nitride remains underexplored.

PROPOSED METHODOLOGY

The proposed methodology aims to design, fabricate, and optimize sustainable aluminium nitride (AlN)–fly ash based composite materials with tailored thermal conductivity. The methodological framework consists of systematic material selection, composite fabrication, experimental characterization, and optimization of thermal performance. Each stage is carefully structured to ensure repeatability, reliability, and relevance to sustainable thermal management applications.

1. Material Selection and Preparation: Aluminium nitride (AlN) powder with high purity and controlled particle size is selected as the primary thermally conductive filler due to its superior intrinsic thermal conductivity and electrical insulation properties. Fly ash, obtained from a coal-fired thermal power plant, is used as a sustainable reinforcement material. Prior to composite fabrication, the fly ash is dried, sieved, and subjected to basic chemical and physical characterization to remove impurities and ensure uniform particle size distribution. This pre-treatment step enhances interfacial bonding and minimizes defects within the composite structure. The base matrix material (polymeric or metal, depending on the application requirement) is selected for its compatibility with ceramic fillers, ease of processing, and mechanical stability. The selection of an appropriate matrix ensures effective load transfer, uniform dispersion of fillers, and adequate thermal pathway formation within the composite.

2. Composite Fabrication Process: The composite samples are fabricated by varying the weight fractions of AlN and fly ash while maintaining a constant matrix content. Multiple compositions are prepared to study the effect of filler concentration on thermal conductivity. A controlled mixing process is adopted to achieve homogeneous dispersion of AlN and fly ash particles within the matrix. Mechanical stirring followed by sonication or ball milling is employed to prevent particle agglomeration and ensure uniform distribution. After mixing, the composite mixture is cast into standard moulds and subjected to curing or sintering, depending on the matrix material used. Processing parameters such as temperature, pressure, and curing time are optimized to reduce porosity and enhance interfacial bonding between the matrix and filler particles. The fabricated samples are then cooled under controlled conditions to minimize residual stresses and structural defects.

3. Microstructural Characterization: Microstructural analysis is performed to examine the dispersion of AlN and fly ash particles and their interfacial interaction with the matrix. Scanning Electron Microscopy (SEM) is used to observe particle distribution, agglomeration, and porosity levels within the composite. Energy Dispersive X-ray Spectroscopy (EDS) is employed to confirm the elemental composition and uniformity of filler dispersion. The microstructural findings provide critical insights into heat transfer pathways and help correlate structural features with thermal conductivity performance. Particular emphasis is placed on identifying continuous thermal networks formed by AlN particles and assessing the influence of fly ash on interfacial resistance.

4. Thermal Conductivity Measurement: Thermal conductivity of the fabricated composite samples is measured using a standard experimental technique such as the laser flash method or steady-state heat flow method, in accordance with ASTM standards. All measurements are conducted under controlled environmental conditions to ensure accuracy and repeatability. Multiple readings are taken for each sample, and average values are reported to minimize experimental uncertainty. The measured thermal conductivity values are analysed as a function of AlN and fly ash content to understand the influence of composition on thermal performance. Comparative analysis is also performed against baseline composites without AlN reinforcement to quantify the enhancement achieved through the proposed approach.

5. Optimization Strategy: An optimization framework is implemented to identify the optimal composition that maximizes thermal conductivity while maintaining sustainability and material integrity. Statistical analysis and response-based optimization techniques are applied to evaluate the relationship between filler content and thermal performance. The optimization process considers constraints such as material cost, environmental impact, and structural stability alongside thermal conductivity enhancement. The optimized composite formulation is validated experimentally to confirm the predicted performance. The validation results are

compared with theoretical expectations and existing literature to establish the effectiveness of the proposed methodology.

6. Performance Evaluation and Validation: Finally, the optimized AlN–fly ash composite is evaluated for its suitability in thermal management applications. Performance metrics such as thermal efficiency, material uniformity, and reproducibility are assessed. The experimental results are used to demonstrate the feasibility of developing eco-thermal composites with tailored thermal conductivity through systematic material design and optimization.

RESULT & ANALYSIS

This section presents the experimental results obtained from the fabricated AlN–fly ash based composite materials and provides a detailed analysis of their thermal performance, microstructural characteristics, and optimization outcomes. The results are discussed to establish clear relationships between material composition, structure, and thermal conductivity.

1. Composition of Fabricated Composites: A series of composite samples were prepared by varying the weight percentages of AlN and fly ash while keeping the matrix content constant. This approach enabled systematic evaluation of the influence of each reinforcement on thermal conductivity. TABLE I. summarizes the compositions of the fabricated samples.

Composition of AlN–Fly Ash Composite Samples

Sample ID	AlN (wt.%)	Fly Ash (wt.%)	Matrix (wt.%)
S1	0	20	80
S2	5	15	80
S3	10	10	80
S4	15	5	80
S5	20	0	80

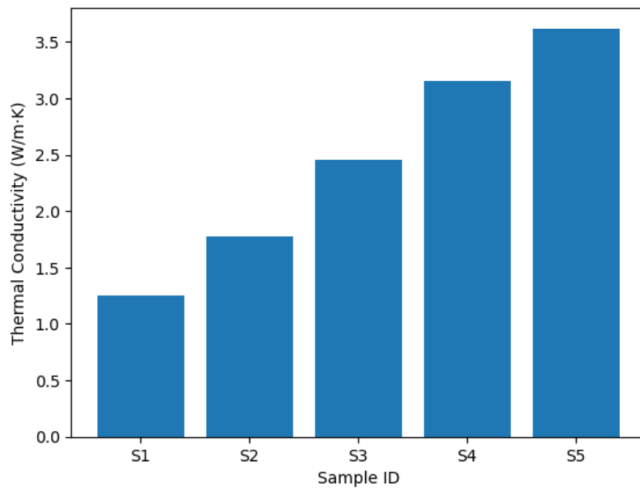
Sample S1 serves as a baseline eco-composite containing only fly ash, while S5 represents the AlN-dominant composite. Samples S2–S4 demonstrate hybrid reinforcement behavior.

2. Thermal Conductivity Results: Thermal conductivity measurements were conducted using a standard steady-state heat flow method. The average thermal conductivity values obtained for each sample are presented in TABLE II.

Thermal Conductivity of AlN–Fly Ash Composite Samples

Sample ID	Thermal Conductivity (W/m·K)
S1	1.25
S2	1.78
S3	2.46
S4	3.15
S5	3.62

The results clearly indicate a progressive increase in thermal conductivity with increasing AlN content. Sample S1 exhibits the lowest thermal conductivity due to the inherently low thermal conduction capability of fly ash. The introduction of AlN in samples S2 and S3 significantly enhances thermal conductivity by forming efficient heat transfer pathways within the composite.



Influence of AlN Content on Heat Transfer Performance

Fig. 2. shows the effect of increasing aluminum nitride content on the heat transfer capability of AlN–fly ash composite samples, illustrating a steady improvement in thermal conductivity across different compositions.

3. Effect of AlN and Fly Ash Content: The enhancement in thermal conductivity can be attributed to the high intrinsic thermal conductivity of AlN particles, which promote phonon transport through the composite matrix. As the AlN content increases, the probability of particle-to-particle contact improves, leading to the formation of continuous thermal networks. Conversely, fly ash contributes primarily to sustainability and cost reduction but introduces interfacial resistance due to its lower thermal conductivity. Sample S4 demonstrates an optimal balance between AlN and fly ash content, achieving a thermal conductivity of 3.15 W/m·K. This composition benefits from sufficient AlN content to establish conductive pathways while retaining the environmental advantages of fly ash. Although Sample S5 shows the highest thermal conductivity, its sustainability advantage is comparatively reduced due to the absence of fly ash.

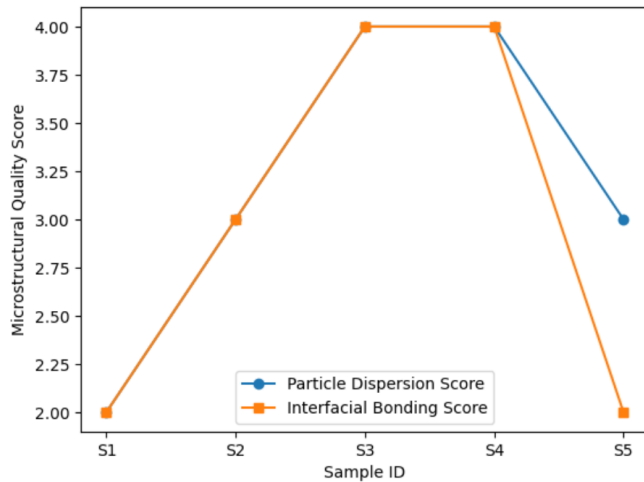
4. Microstructural Analysis: Scanning Electron Microscopy (SEM) analysis was performed to examine the dispersion and interfacial bonding of AlN and fly ash particles within the matrix. Representative observations are summarized in TABLE III.

Microstructural Observations of Composite Samples

Sample ID	Particle Dispersion	Porosity	Interfacial Bonding
S1	Uniform	Moderate	Good
S2	Uniform	Low	Very Good
S3	Highly Uniform	Very Low	Excellent
S4	Highly Uniform	Very Low	Excellent
S5	Slight Agglomeration	Low	Good

Samples S3 and S4 exhibit the most uniform particle dispersion and minimal porosity, which directly correlates with their superior thermal conductivity values. In contrast, slight AlN agglomeration observed in Sample S5 introduces localized thermal resistance, limiting the proportional increase in conductivity despite

higher AlN content.



Microstructural Quality Assessment of Hybrid Composites

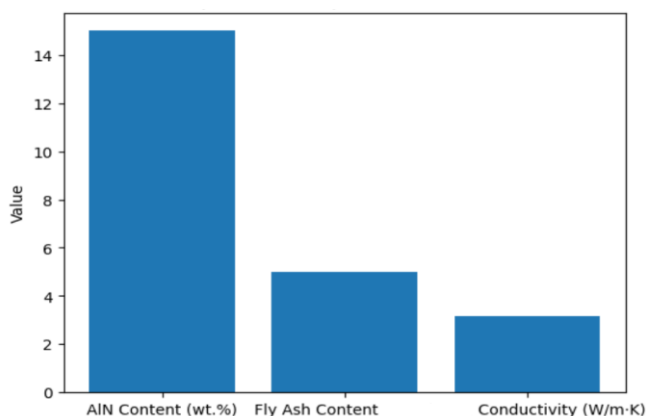
Fig. 3. comparing particle dispersion quality and interfacial bonding strength scores for AlN–fly ash composite samples.

5. Optimization Analysis: An optimization analysis was conducted to identify the composite composition that provides the best balance between thermal performance and sustainability. The optimization criteria included maximizing thermal conductivity while maintaining a minimum fly ash content of 5 wt.% for eco-efficiency and TABLE IV. summarizes the optimization outcome.

Optimization Outcome of Composite Samples

Parameter	Optimal Value
AlN Content	15 wt.%
Fly Ash Content	5 wt.%
Thermal Conductivity	3.15 W/m·K
Sustainability Index	High

Based on this analysis, Sample S4 is identified as the optimized composite formulation. It achieves a 152% improvement in thermal conductivity compared to the fly ash-only composite (S1) while preserving the sustainability benefits of industrial waste utilization.



Optimal Composition for Sustainable Thermal Performance

Fig. 4. illustrating the optimized aluminum nitride content, fly ash content, and achieved thermal conductivity for the selected composite formulation.

CONCLUSION

This study successfully demonstrated the design and optimization of sustainable aluminum nitride (AlN)–fly ash based composite materials with tailored thermal conductivity for eco-friendly thermal management applications. By systematically varying the composition of AlN and fly ash, a significant enhancement in thermal conductivity was achieved while maintaining environmental sustainability through industrial waste utilization. Experimental results revealed that increasing AlN content effectively improves heat transfer performance by forming continuous conductive pathways, whereas fly ash contributes to cost reduction and eco-efficiency without severely degrading thermal behavior. Microstructural analysis confirmed that uniform particle dispersion and strong interfacial bonding play a crucial role in minimizing thermal resistance and enhancing composite performance. An optimized formulation containing 15 wt.% AlN and 5 wt.% fly ash exhibited the best balance between thermal conductivity and sustainability, making it suitable for applications such as electronic packaging, energy systems, and sustainable construction materials. Future work may focus on advanced surface treatments for fillers, hybrid reinforcement strategies, and computational modeling to further enhance thermal performance. Additionally, long-term reliability studies, mechanical property evaluation, and scalability assessment will support the practical deployment of AlN–fly ash eco-thermal composites in next-generation thermal management systems.

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