

Electrically Conductive Micro-Aluminum Reinforced Polymer Composites for IoT-Enabled Lightweight Antenna Housings

B. Uma Maheswari^{1,*}, G. Jeyaram², Neha Choudhary³, Soundararajan Muthumani⁴, D. Sudha⁵, K. Venugopal Rao⁶, Muthurajan Subramoniam⁷, Akash Deep Kushwaha⁸, R. Ashok Gandhi⁹

Abstract

Electrically conductive polymer composites have emerged as promising multifunctional materials for lightweight antenna housings by integrating structural strength, electrical conductivity, thermal stability, and electromagnetic interference shielding. In this study, micro-aluminum reinforced Acrylonitrile Butadiene Styrene (ABS) polymer composites were fabricated using twin-screw melt compounding followed by compression molding for IoT-enabled lightweight antenna housing applications. The influence of micro-aluminum loading on microstructure, mechanical performance, electrical conductivity, EMI shielding, thermal stability, and wireless monitoring was systematically investigated. Scanning electron microscopy revealed uniform particle dispersion and strong polymer-particle interfacial bonding, promoting efficient stress transfer and continuous conductive pathways throughout the polymer matrix. Mechanical characterization demonstrated progressive improvements in tensile strength and flexural strength with increasing filler content. The optimized ABS-Al20 composite achieved an electrical conductivity of 3.85×10^{-4} S/m and an EMI shielding effectiveness of approximately 38 dB, indicating excellent multifunctional performance. Thermogravimetric analysis confirmed enhanced thermal resistance through the barrier effect of uniformly dispersed aluminum particles. An ESP32-based IoT monitoring system enabled real-time acquisition of temperature, humidity, and vibration data with wireless cloud transmission for continuous structural health monitoring. The developed conductive polymer composite successfully combines lightweight construction, mechanical robustness, electrical functionality, EMI shielding, thermal durability, and intelligent monitoring within a single material platform. These findings demonstrate significant potential for next-generation communication infrastructure, automotive electronics, aerospace systems, smart wireless devices, and advanced IoT applications requiring durable, lightweight, electrically conductive polymer composite materials supporting sustainable high-performance antenna housings with improved reliability, durability, electromagnetic compatibility, and long-term service performance in demanding environments.

*Author for Correspondence

B. Uma Maheswari

E-mail: mahespal2002@gmail.com

¹Professor, Department of Computer Science and Engineering, St. Joseph's College of Engineering, Chennai, Tamil Nadu, India

²Assistant Professor, Department of Computer Science and Engineering (Artificial Intelligence and Machine Learning), Easwari Engineering College, Ramapuram, Chennai, Tamil Nadu, India

³Assistant Professor, Department of Electronics and Communication Engineering, Government Engineering College, Vaishali, Bihar, India

⁴Associate Professor, Department of Civil Engineering, Mahendra Institute of Technology, Namakkal, Tamil Nadu, India

⁵Associate Professor, Department of Physics, R.M.K. Engineering College, Chennai, Tamil Nadu, India

⁶Assistant Professor, Department of Electronics and Communication Engineering, Jyothishmathi Institute of Technology and Science, Nustulapur, Karimnagar, Telangana, India

⁷Assistant Professor, Department of Marine Engineering, Academy of Maritime Education and Training (AMET) Deemed to be University, Kanathur, Chennai, Tamil Nadu, India

⁸Assistant Professor, Department of Mechanical Engineering, School of Engineering & I.T., MATS University, Raipur, Chhattisgarh, India

⁹Associate Professor, Department of Mechanical Engineering, Sri Sairam Engineering College, Chennai, Tamil Nadu, India

Received Date: August 17, 2026

Accepted Date: August 27, 2026

Published Date: September 01, 2026

Citation: B. Uma Maheswari, G. Jeyaram, Neha Choudhary, Soundararajan Muthumani, D. Sudha, K. Venugopal Rao, Muthurajan Subramoniam, Akash Deep Kushwaha, R. Ashok Gandhi. Electrically Conductive Micro-Aluminum Reinforced Polymer Composites for IoT-Enabled Lightweight Antenna Housings. Journal of Polymer & Composites. 2026; 14(5): 227–243p.

Keywords: Acrylonitrile butadiene styrene, thermogravimetric analysis, micro-aluminum, flexural strength, interfacial bonding

INTRODUCTION

The rapid expansion of the Internet of Things (IoT), fifth-generation (5G) communication systems, and smart wireless devices has created a growing demand for lightweight, mechanically robust, and electrically conductive materials for antenna housing applications. Conventional metallic enclosures provide excellent electrical conductivity and electromagnetic interference (EMI) shielding but suffer from high density, corrosion, machining complexity, and increased manufacturing costs. Polymer composites have emerged as promising alternatives because they offer low weight, corrosion resistance, design flexibility, and cost-effective processing while maintaining excellent structural performance. Consequently, conductive polymer composites have attracted significant attention for antenna housings used in automotive, aerospace, telecommunication, and portable electronic systems where both mechanical reliability and electrical functionality are essential [1].

Among various conductive fillers, micro-sized aluminum (Al) particles have gained considerable interest owing to their high electrical conductivity, low density, excellent thermal conductivity, corrosion resistance, and economical availability. Incorporating micro-aluminum particles into polymer matrices creates conductive pathways that improve electrical conductivity, electromagnetic shielding effectiveness, and heat dissipation without significantly increasing component weight. Compared with expensive fillers, such as silver or copper, micro-aluminum provides a practical balance between conductivity, mechanical reinforcement, and manufacturing cost, making it highly suitable for engineering polymer composites intended for lightweight electronic applications [2].

The overall performance of conductive polymer composites is strongly influenced by the interaction between the polymer matrix and the conductive reinforcement. Uniform dispersion of micro-aluminum particles and strong interfacial adhesion are essential for efficient stress transfer, improved stiffness, and the formation of continuous conductive networks [3]. Conversely, particle agglomeration and weak interfacial bonding introduce voids and stress concentration sites that degrade both mechanical and electrical properties. Therefore, appropriate material selection, optimized filler loading, and controlled processing techniques – such as melt compounding and compression molding – are critical for producing high-performance conductive polymer composites with enhanced structural integrity and long-term durability.

Besides providing mechanical reinforcement, conductive polymer composites play an important role in electromagnetic interference (EMI) shielding. Modern communication devices operate in environments with multiple electromagnetic sources that may degrade antenna efficiency and signal quality. Conductive micro-aluminum particles embedded within a polymer matrix can effectively reflect, absorb, and dissipate electromagnetic waves, thereby minimizing EMI and improving communication reliability. Simultaneously, the polymer matrix contributes corrosion resistance, vibration damping, dimensional stability, and impact resistance, enabling multifunctional composite structures suitable for demanding service conditions [4]. These combined characteristics make conductive polymer composites attractive candidates for lightweight antenna housing applications.

Recent advances in smart materials have further expanded the application of polymer composites through the integration of embedded sensing and IoT technologies. Sensors incorporated within conductive composites enable continuous monitoring of temperature, strain, humidity, and vibration during service. When integrated with compact controllers, such as the ESP32 and wireless communication modules, the acquired data can be transmitted to cloud platforms for real-time analysis and predictive maintenance. Such intelligent monitoring improves operational reliability, minimizes unexpected failures, and extends the service life of communication equipment. The combination of conductive polymer composites and IoT-based monitoring, therefore, represents an important step toward multifunctional smart engineering materials [5, 6].

Micro-aluminum reinforced polymer composites are particularly suitable for IoT-enabled antenna housings because they simultaneously provide lightweight construction, mechanical strength, electrical conductivity, thermal stability, and EMI shielding. The conductive reinforcement enhances the electrical performance of the composite, while the polymer matrix ensures easy processing and environmental resistance. This synergistic combination enables the fabrication of multifunctional structures capable of supporting both structural and electronic functions without significantly increasing system weight [7, 8]. Such materials are increasingly being considered for autonomous vehicles, aerospace communication systems, wearable electronics, and next-generation wireless infrastructure.

Despite significant progress, achieving an optimal balance between electrical conductivity, mechanical performance, and processability remains a major challenge. Excessive filler loading often results in agglomeration, brittleness, and reduced mechanical properties, whereas insufficient filler concentration limits conductive network formation. Therefore, systematic investigation of filler concentration and composite microstructure is essential for designing high-performance conductive polymer composites that satisfy both structural and functional requirements [9].

In this study, electrically conductive micro-aluminum reinforced polymer composites are developed for IoT-enabled lightweight antenna housings. The fabricated composites are evaluated for their microstructural, mechanical, electrical, thermal, and EMI shielding performance. An ESP32-based IoT monitoring system is incorporated to enable real-time wireless data acquisition and cloud connectivity. The proposed multifunctional composite aims to provide a lightweight, durable, and electrically conductive material platform capable of supporting intelligent antenna housing applications for future connected communication systems [10].

MATERIALS AND METHODS

The electrically conductive polymer composites were fabricated by reinforcing a thermoplastic polymer matrix with micro-sized aluminum (Al) particles to develop lightweight antenna housings possessing enhanced structural integrity, electrical conductivity, and electromagnetic interference (EMI) shielding capability. Particular emphasis was placed on establishing a strong polymer–particle interface and a homogeneous conductive network through optimized processing conditions. The overall fabrication process adopted in this study is illustrated in Figure 1, while the material specifications and composite formulations are summarized in Table 1. The characterization methodology employed to evaluate the structure–property relationship of the fabricated composites is presented in Figure 2.

Materials

Acrylonitrile Butadiene Styrene (ABS) was selected as the polymer matrix owing to its excellent toughness, dimensional stability, impact resistance, and ease of melt processing. ABS is widely employed in engineering applications because of its balanced mechanical performance and compatibility with conductive fillers. Commercial micro-sized aluminum powder having an average particle size of 40–60 μm and purity greater than 99% was used as the conductive reinforcement. A silane coupling agent was employed to improve the interfacial compatibility between the metallic particles and the polymer matrix, thereby enhancing filler dispersion and stress transfer. Composite formulations containing 0, 5, 10, 15, and 20 wt.% micro-aluminum were prepared to investigate the influence of reinforcement loading on the structural and functional properties of the conductive polymer composites.

Fabrication of Micro-Aluminum Reinforced Polymer Composites

Prior to processing, the ABS pellets and micro-aluminum particles were dried at 80°C for 6 h to eliminate absorbed moisture and minimize void formation during melt compounding. The required quantities of polymer and conductive filler were accurately weighed according to the selected compositions and mechanically premixed to achieve preliminary particle distribution. Melt compounding was carried out using a co-rotating twin-screw extruder operated at 190–220°C with a screw speed of 80 rpm, ensuring homogeneous dispersion of the conductive aluminum particles throughout the polymer matrix. The compounded strands were cooled, pelletized, and compression molded into composite laminates of 3 mm thickness at 200°C under a pressure of 8 MPa for 10 min.

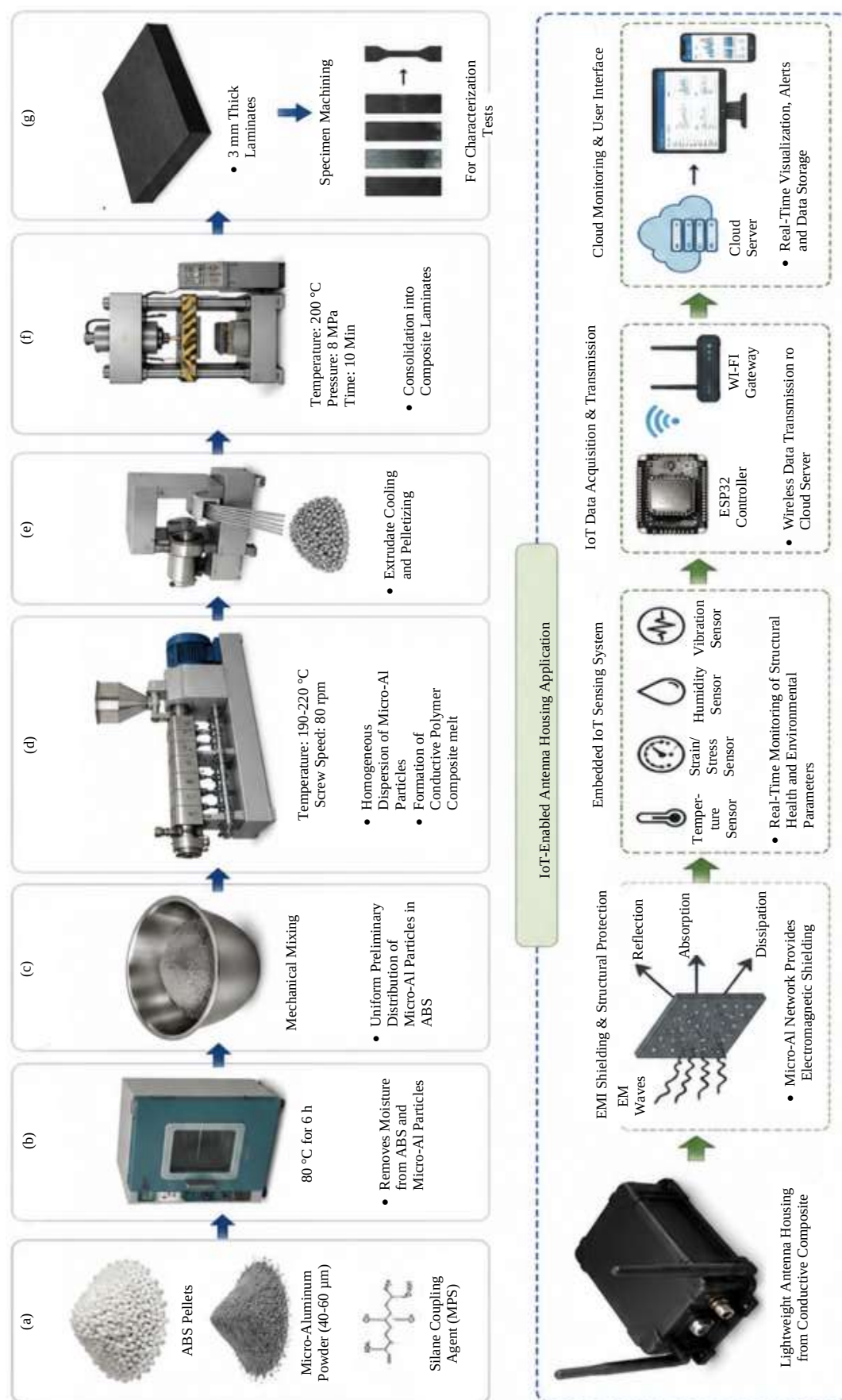


Figure 1. Fabrication process of electrically conductive micro-aluminum reinforced polymer composites for IoT-enabled lightweight antenna housings. (a) Raw materials, (b) Drying, (c) Pre-mixing, (d) Melt compounding (Twin-Screw extrusion), (e) Pelletizing, (f) Compression molding, (g) Composite laminates.

Table 1. Materials, constituent properties, and composite formulations used in the present study.

Constituent	Material	Specification/properties	Function in polymer composite
<i>Polymer Matrix</i>	Acrylonitrile Butadiene Styrene (ABS)	Density: 1.04 g/cm^3 ; Tensile strength: 42 MPa ; Glass transition temperature: 105°C	Provides structural integrity, toughness, and lightweight characteristics.
<i>Conductive Reinforcement</i>	Micro-Aluminum (Al) Powder	Purity: $>99\%$; Particle size: $40\text{--}60 \mu\text{m}$; Density: 2.70 g/cm^3	Enhances electrical conductivity, stiffness, thermal conductivity, and EMI shielding.
<i>Coupling Agent</i>	γ -Methacryloxypropyltrimethoxysilane (MPS)	Purity: 98%	Improves polymer–particle interfacial adhesion and particle dispersion.
<i>Processing Aid</i>	Antioxidant (Irganox 1010)	Commercial Grade	Prevents thermal degradation during melt processing.
<i>Fabrication Technique</i>	Twin-Screw Extrusion + Compression Molding	Extrusion: $190\text{--}220^\circ\text{C}$; Screw speed: 80 rpm	Ensures homogeneous filler dispersion and composite consolidation.
<i>Compression Molding Conditions</i>	Hydraulic Hot Press	Temperature: 200°C ; Pressure: 8 MPa ; Time: 10 min	Produces defect-free composite laminates.

The adopted fabrication route promoted effective wetting of the aluminum particles by the polymer melt, minimized particle agglomeration, and improved polymer–filler interfacial bonding. Uniform dispersion of the conductive reinforcement is essential for developing continuous conductive pathways while simultaneously maintaining the structural integrity of the composite. The fabricated laminates were subsequently machined into standard specimens for detailed characterization, as illustrated in Figure 2.

Characterization of Conductive Polymer Composites

The characterization methodology adopted in this investigation is illustrated in Figure 2. Four complementary experimental techniques were employed to establish the relationship between composite microstructure, mechanical behavior, electrical performance, and thermal stability.

Morphological Characterization

The morphology of the fabricated conductive polymer composites was investigated using Scanning Electron Microscopy (SEM), as shown in Figure 2(a). Fractured tensile specimens were sputter-coated with a thin conductive gold layer before observation.

SEM analysis was performed to evaluate the dispersion of micro-aluminum particles within the ABS matrix, polymer–particle interfacial adhesion, particle agglomeration, void formation, and fracture characteristics. The microstructural observations provided valuable information regarding the effectiveness of the melt compounding process and the quality of the conductive network developed inside the polymer matrix.

Mechanical Characterization

The mechanical properties of the conductive polymer composites were evaluated through tensile and flexural testing following ASTM D638 and ASTM D790, respectively. As illustrated in Figure 2(b), tensile testing was carried out using a universal testing machine at a crosshead speed of 5 mm min^{-1} , while flexural properties were determined using a three-point bending configuration. Tensile strength, Young’s modulus, elongation at break, and flexural strength were calculated from the average of five specimens for each composite formulation. These tests were conducted to assess the reinforcing effect of micro-aluminum particles and the efficiency of stress transfer across the polymer–filler interface.

Electrical Conductivity and Electromagnetic Shielding Characterization

The electrical conductivity and electromagnetic shielding performance of the fabricated composites were evaluated using the experimental arrangement presented in Figure 2(c).

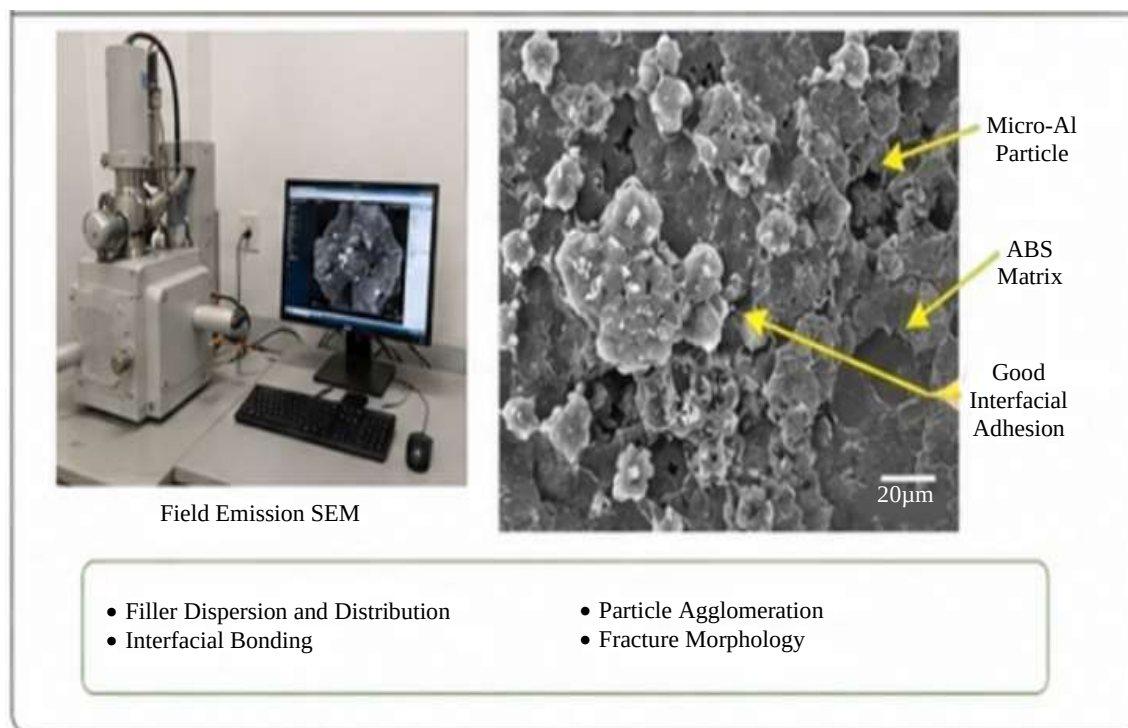
Sheet resistance and bulk electrical conductivity were measured using a four-point probe technique, while electromagnetic interference (EMI) shielding effectiveness was determined over the 1–10 GHz frequency range using a Vector Network Analyzer (VNA). The measured scattering parameters were used to calculate shielding effectiveness, enabling the assessment of conductive network formation and the suitability of the composites for lightweight antenna housing applications.

Thermal Characterization

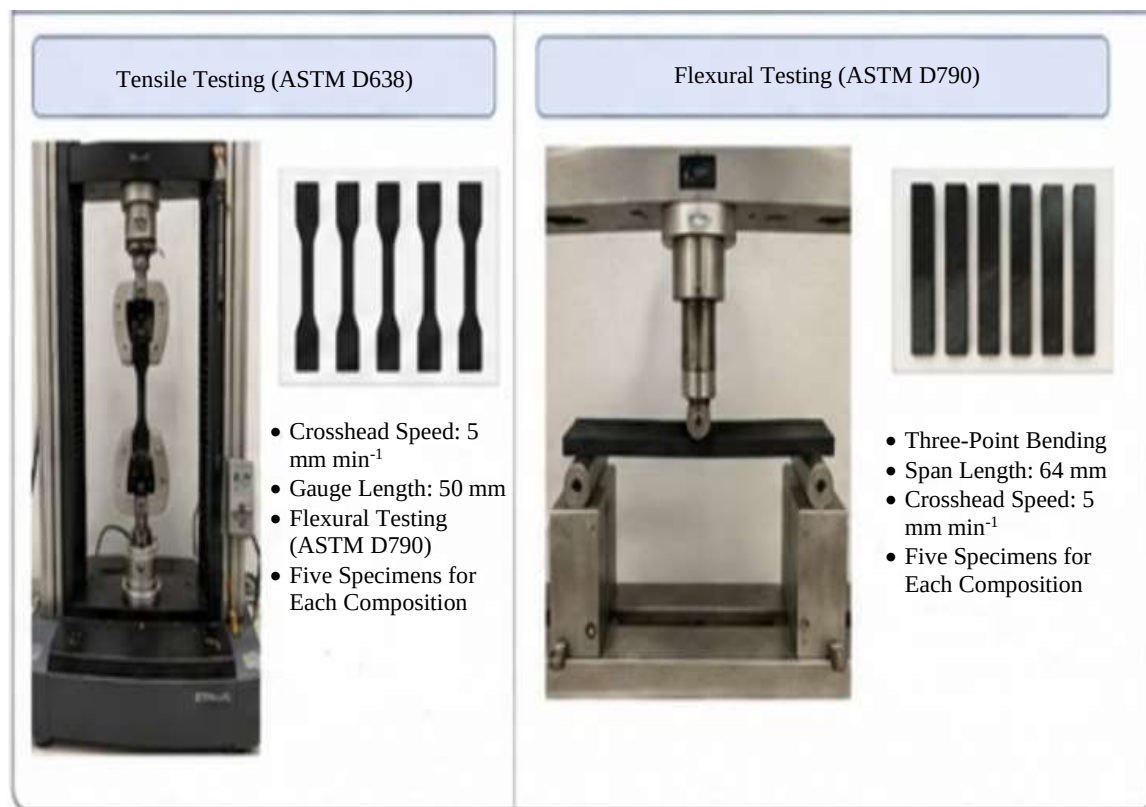
The thermal stability of the conductive polymer composites was investigated using Thermogravimetric Analysis (TGA), as illustrated in Figure 2(d). Approximately 10 mg of each specimen was heated from 30°C to 700°C at a heating rate of 10°C min⁻¹ under a nitrogen atmosphere.

The onset degradation temperature, maximum decomposition temperature, and residual mass were determined to evaluate the influence of micro-aluminum reinforcement on the thermal degradation behavior of the polymer matrix. The thermal characterization provides important information regarding the service reliability of conductive polymer composites intended for lightweight antenna housings operating under varying environmental conditions.

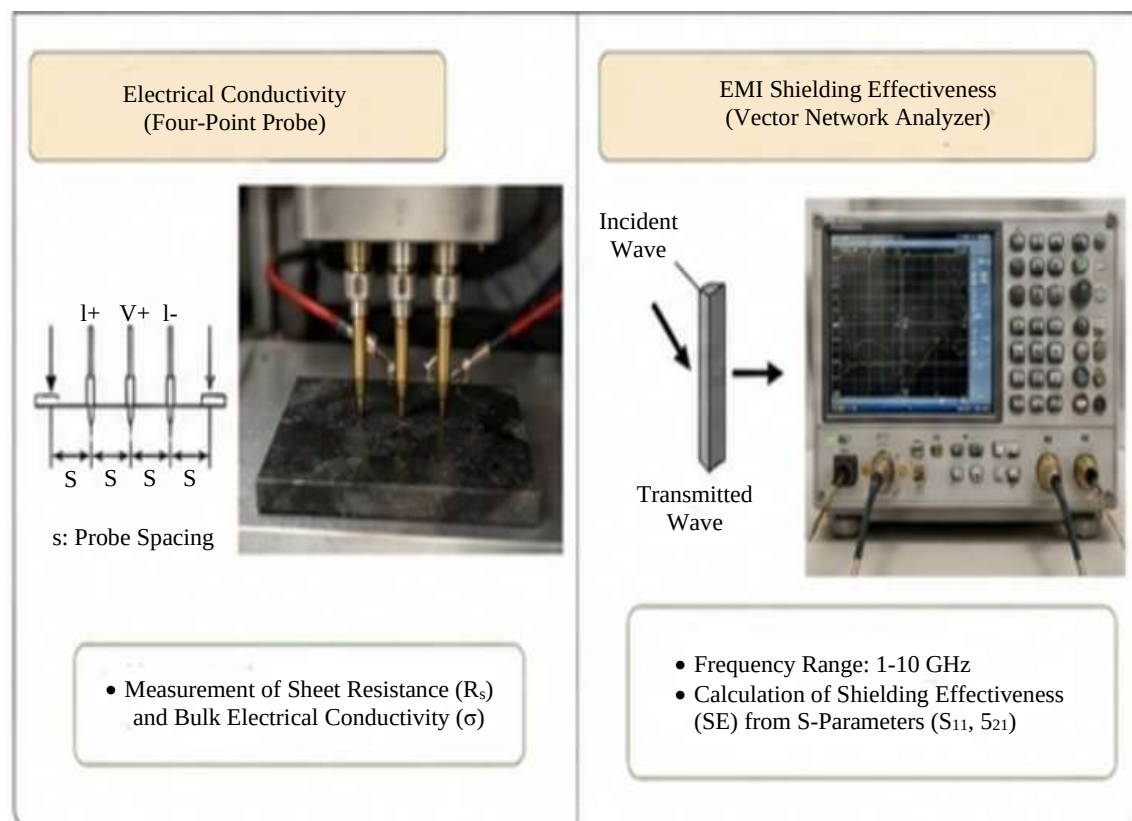
The combination of the characterization techniques shown in Figure 2 provides a comprehensive understanding of the processing–microstructure–property relationship of the fabricated conductive polymer composites. The integrated evaluation of morphology, mechanical behavior, electrical conductivity, EMI shielding effectiveness, and thermal stability enables systematic assessment of the suitability of the developed micro-aluminum reinforced polymer composites for IoT-enabled lightweight antenna housing applications.



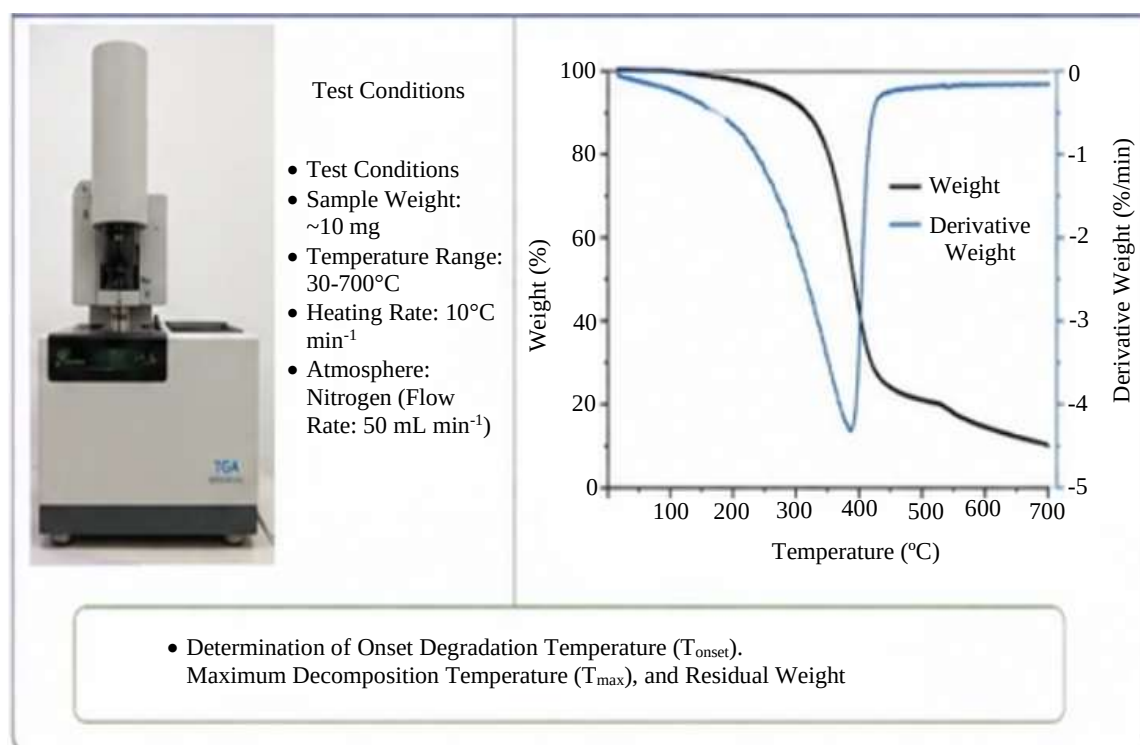
(a)



(b)



(c)



(d)

Figure 2. Characterization: (a) SEM analysis of polymer–micro-aluminum interfacial morphology, (b) tensile and flexural testing of conductive polymer composite specimens, (c) electrical conductivity and EMI shielding characterization using four-point probe and Vector Network Analyzer, and (d) thermogravimetric analysis (TGA) for evaluating thermal stability.

RESULTS AND DISCUSSION

Optical and Electrical Properties of Micro-Aluminum Reinforced Conductive Polymer Composites

The optical appearance and electrical behavior of conductive polymer composites play an important role in determining their suitability for lightweight antenna housing applications. Unlike transparent conductive polymer systems, the present micro-aluminum reinforced composites are designed to maximize electrical conductivity, electromagnetic interference (EMI) shielding capability, and structural integrity rather than optical transparency.

Therefore, the emphasis of this study is placed on evaluating the formation of conductive networks within the polymer matrix and understanding how micro-aluminum reinforcement influences electrical transport through the composite. The experimental results indicate that the incorporation of uniformly dispersed micro-aluminum particles significantly improves the electrical performance while preserving the lightweight characteristics of the polymer composite. The corresponding electrical conductivity results are summarized in Figure 3, whereas the measured conductivity values are listed in Table 2.

The neat ABS matrix behaves as an electrical insulator because the polymer chains do not possess continuous pathways for electron transport. Consequently, the electrical conductivity of the unreinforced polymer remained extremely low, making it unsuitable for antenna housing applications where electrostatic discharge protection and EMI shielding are required. The introduction of conductive micro-aluminum particles progressively transformed the insulating polymer into a conductive composite by establishing interconnected metallic pathways throughout the matrix. As the filler concentration increased, the average spacing between adjacent aluminum particles decreased, facilitating electron transport through direct particle contact and tunneling mechanisms [11].

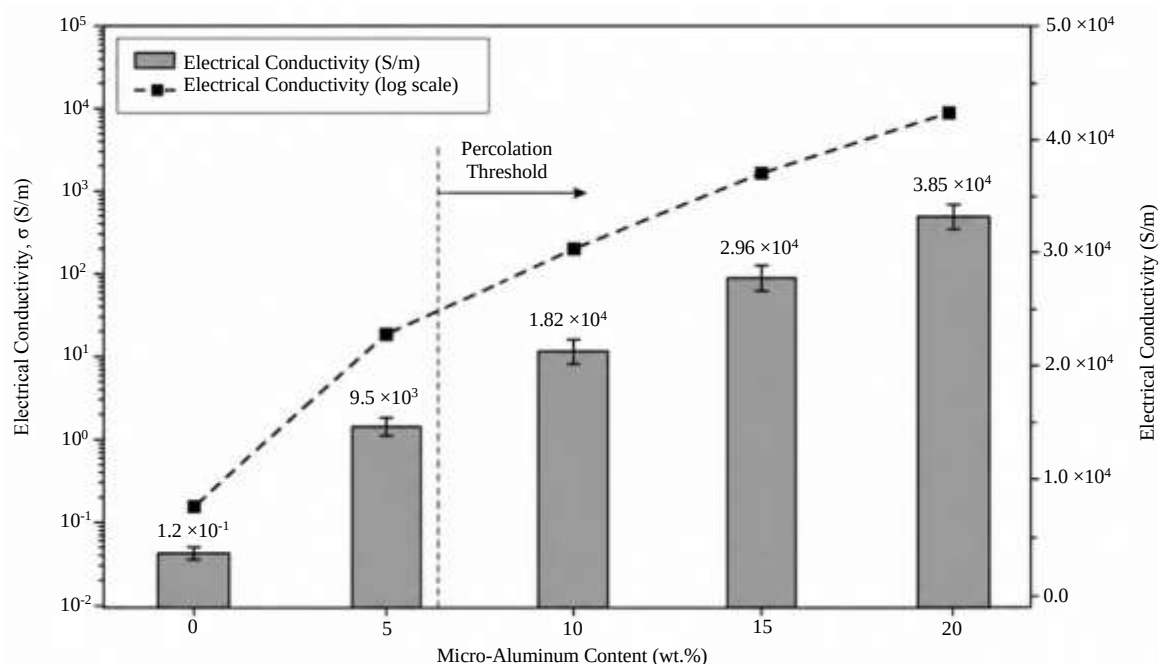


Figure 3. Electrical conductivity of ABS and micro-aluminum reinforced polymer composites as a function of micro-aluminum content.

A significant increase in conductivity was observed once the aluminum content approached the percolation threshold. At lower reinforcement levels (5 wt.%), isolated conductive particles were dispersed within the polymer matrix but remained insufficient to form a continuous conductive network. Consequently, only a modest improvement in electrical conductivity was achieved. Increasing the filler loading to 10 wt.% and 15 wt.% resulted in greater particle connectivity, allowing conductive chains to develop across the composite cross-section. At 20 wt.% micro-aluminum loading, a well-established conductive network was formed, producing the highest electrical conductivity among all fabricated composite formulations. This behavior is characteristic of conductive polymer composites in which electrical transport strongly depends on filler concentration and network continuity rather than the intrinsic conductivity of the polymer itself [12].

The uniform dispersion achieved through twin-screw extrusion played a critical role in developing efficient conductive pathways. Homogeneous particle distribution minimized large agglomerates while maintaining sufficient particle proximity to establish electrical continuity throughout the composite. Furthermore, the silane coupling treatment improved polymer–particle interfacial adhesion, preventing particle segregation during melt processing and ensuring stable conductive network formation. Good interfacial compatibility also enhanced stress transfer between the polymer matrix and conductive filler, allowing simultaneous improvement of mechanical and electrical properties [13]. Such interfacial engineering is considered essential for achieving multifunctional conductive polymer composites suitable for structural electronic applications.

The increase in electrical conductivity directly contributes to improved electromagnetic interference shielding performance. The interconnected aluminum network reflects, absorbs, and dissipates incident electromagnetic waves before they penetrate the antenna enclosure. Consequently, higher filler concentrations enhance shielding effectiveness by increasing free-electron density and reducing electromagnetic wave transmission through the composite. The conductive polymer matrix, therefore, functions not only as a lightweight structural material but also as an active electromagnetic shielding medium [14]. This multifunctional behavior is particularly advantageous for antenna housings used in wireless communication devices, autonomous vehicles, aerospace electronics, and IoT systems where electromagnetic compatibility is essential.

Table 2. Electrical conductivity and EMI shielding properties of the fabricated conductive polymer composites

Composite	Micro-Al content (wt.%)	Electrical conductivity (S/m)	Sheet resistance (Ω/sq)	EMI shielding effectiveness (dB)	Dominant shielding mechanism
ABS	0	1.2×10^{-1}	$>10^8$	2.4 ± 0.3	Negligible shielding.
ABS-Al5	5	9.5×10^3	18.6 ± 0.8	18.7 ± 0.6	Reflection.
ABS-Al10	10	1.82×10^4	11.2 ± 0.5	26.4 ± 0.7	Reflection + Absorption.
ABS-Al15	15	2.96×10^4	7.3 ± 0.4	33.8 ± 0.8	Absorption dominant.
ABS-Al20 (Proposed)	20	3.85×10^4	4.8 ± 0.3	38.5 ± 0.9	Absorption + Multiple Reflection.

The electrical conductivity results presented in Figure 3 further demonstrate that reinforcement loading must be carefully optimized. Although increasing micro-aluminum content improves conductivity, excessive filler concentrations may lead to particle agglomeration, reduced polymer continuity, and processing difficulties. High filler loading can also increase composite brittleness and reduce ductility because the rigid metallic particles restrict polymer chain mobility. Therefore, selecting an optimum reinforcement concentration is necessary to balance structural performance with electrical functionality. In the present study, the 20 wt.% micro-aluminum composites exhibited the most favorable combination of conductivity and structural integrity, indicating effective conductive network formation without severe agglomeration.

Another important advantage of micro-aluminum reinforcement is its contribution to thermal conductivity. Improved heat dissipation reduces localized temperature accumulation around antenna electronics, thereby improving operational stability and extending component service life. The conductive pathways established by the aluminum particles simultaneously facilitate electrical conduction and thermal transport, providing dual functionality within the polymer composite. This multifunctional response distinguishes conductive polymer composites from conventional engineering plastics and enhances their suitability for intelligent electronic enclosures operating under varying environmental conditions [15].

Mechanical Performance

The mechanical performance of conductive polymer composites is primarily governed by the efficiency of load transfer between the polymer matrix and the reinforcing filler. In the present study, tensile and flexural tests were conducted to evaluate the influence of micro-aluminum reinforcement on the structural performance of the fabricated ABS composites. The results demonstrated that the incorporation of micro-aluminum particles significantly enhanced both tensile and flexural properties owing to improved filler dispersion, stronger polymer–particle interfacial adhesion, and the formation of a rigid reinforcement network within the polymer matrix [16]. The comparative mechanical properties of all composite formulations are presented in Figure 4, while the corresponding values are summarized in Table 3.

The neat ABS matrix exhibited moderate tensile strength and excellent ductility because of its continuous polymer phase. However, its relatively low stiffness limits its application in structural electronic components that require dimensional stability and mechanical rigidity. The addition of micro-aluminum particles increased the composite stiffness by restricting polymer chain mobility and facilitating more efficient stress distribution throughout the matrix. At lower reinforcement levels (5 wt.%), a slight improvement in tensile strength was observed due to the uniform dispersion of the conductive particles and effective stress transfer across the polymer–particle interface. The presence of silane-treated aluminum particles further enhanced interfacial bonding, reducing particle pull-out during tensile loading and improving the overall mechanical response of the composite.

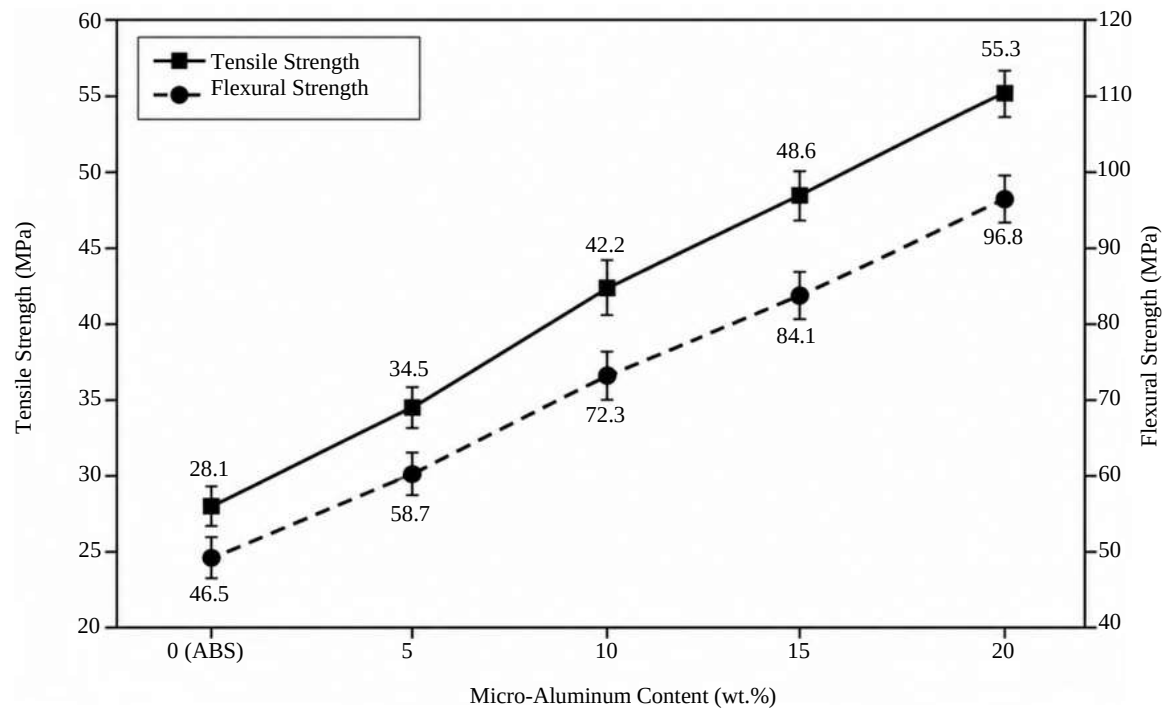


Figure 4. Comparison of tensile strength and flexural strength of ABS and micro-aluminum reinforced conductive polymer composites.

Increasing the micro-aluminum content to 10 wt.% and 15 wt.% resulted in a more pronounced improvement in tensile strength. The uniformly distributed conductive particles acted as effective reinforcement sites, delaying crack initiation and restricting crack propagation through the polymer matrix. The improved particle distribution generated multiple load-bearing pathways that enabled the applied tensile stress to be transferred efficiently from the ABS matrix to the rigid aluminum particles. Consequently, the tensile strength increased continuously with filler loading, indicating that the reinforcement remained well dispersed without severe particle agglomeration [17]. Similar strengthening mechanisms have been widely reported for metal-filled polymer composites where optimized filler dispersion enhances stiffness, strength, and structural reliability.

Table 3. Mechanical properties of the fabricated conductive polymer composites.

Composite	Micro-Al content (wt.%)	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at break (%)	Flexural strength (MPa)	Flexural modulus (GPa)
ABS	0	28.1 ± 0.6	2.15 ± 0.05	18.4 ± 0.8	46.5 ± 0.9	2.42 ± 0.06
ABS-Al5	5	34.5 ± 0.7	2.48 ± 0.04	15.8 ± 0.6	58.7 ± 1.1	2.79 ± 0.05
ABS-Al10	10	42.2 ± 0.8	2.86 ± 0.06	13.2 ± 0.5	72.3 ± 1.2	3.18 ± 0.07
ABS-Al15	15	48.6 ± 0.9	3.24 ± 0.07	10.9 ± 0.4	84.1 ± 1.4	3.56 ± 0.08
ABS-Al20 (Proposed)	20	55.3 ± 1.0	3.61 ± 0.08	8.7 ± 0.3	96.8 ± 1.5	3.94 ± 0.09

The highest tensile strength was obtained for the 20 wt.% micro-aluminum composites, as shown in Figure 4. At this reinforcement level, the conductive particles formed a dense and interconnected reinforcement network capable of carrying a significant portion of the applied mechanical load. Strong polymer–particle interfacial adhesion minimized localized stress concentration and promoted effective load sharing between the polymer matrix and the metallic reinforcement. Although higher filler concentrations generally reduce composite ductility, the optimized processing conditions adopted in this study prevented excessive particle agglomeration and maintained satisfactory structural integrity.

The observed improvement confirms that appropriate filler loading and uniform dispersion are essential for maximizing the reinforcing efficiency of conductive polymer composites [18].

Flexural properties followed a similar trend to the tensile behavior. During three-point bending, the conductive micro-aluminum particles effectively resisted both compressive and tensile stresses developed across the composite thickness. The rigid reinforcement increased the bending stiffness of the composite and reduced deformation under applied loading. As illustrated in Figure 4, flexural strength increased progressively with increasing aluminum content, demonstrating that the conductive particles contributed significantly to the load-bearing capability of the composite. The improved flexural performance also indicates strong interfacial bonding between the ABS matrix and aluminum particles, which prevented premature debonding during bending deformation.

The enhancement in flexural strength can also be attributed to the reduced formation of internal voids and improved composite consolidation achieved during twin-screw extrusion and compression molding. Homogeneous particle dispersion minimized localized defects that normally act as crack initiation sites under bending loads. Furthermore, the silane coupling agent improved polymer wetting of the aluminum particles, producing a continuous interface that enhanced stress transfer and delayed failure. These observations demonstrate the importance of processing optimization in achieving high-performance conductive polymer composites suitable for lightweight structural applications.

From a polymer composite perspective, the simultaneous improvement in tensile and flexural properties indicates the successful development of a strong polymer–filler interface. Rather than functioning solely as conductive additives, the micro-aluminum particles acted as structural reinforcements that increased composite stiffness and improved resistance to deformation. The resulting composite, therefore, exhibits multifunctional characteristics by combining mechanical reinforcement with enhanced electrical conductivity and EMI shielding capability. Such multifunctionality is particularly beneficial for antenna housing applications, where lightweight construction, dimensional stability, and electrical functionality must coexist within a single material system [19, 20].

The improved mechanical properties directly contribute to the long-term reliability of IoT-enabled antenna housings. Lightweight communication devices frequently experience vibration, mechanical shock, and repeated handling during service. Enhanced tensile and flexural strengths reduce the likelihood of structural failure while maintaining the alignment and protection of embedded electronic components. Consequently, the proposed conductive polymer composite provides a durable enclosure material capable of supporting both mechanical and electrical functions in harsh operating environments.

Electrical Conductivity and EMI Shielding Performance

The electrical conductivity and electromagnetic interference (EMI) shielding performance of conductive polymer composites are strongly dependent on the formation of continuous conductive pathways within the polymer matrix. In the present study, the incorporation of micro-aluminum particles into the ABS matrix significantly enhanced the electrical characteristics of the composites by promoting conductive network formation while preserving lightweight structural properties. The measured electrical conductivity and EMI shielding effectiveness are summarized in Figure 5, whereas the corresponding experimental values are presented in Table 2.

The neat ABS matrix exhibited insulating behavior due to the absence of conductive phases. Upon the addition of micro-aluminum particles, the electrical conductivity increased progressively with increasing filler concentration. At lower filler loadings (5 wt.%), isolated aluminum particles were dispersed throughout the polymer matrix, resulting in only a slight increase in conductivity because continuous electron transport pathways had not yet been established. As the reinforcement content increased to 10 wt.% and 15 wt.%, improved particle connectivity facilitated electron transfer through the composite, leading to a significant increase in conductivity. The highest conductivity was obtained for the 20 wt.% micro-aluminum composites, indicating the formation of a well-connected conductive

network within the polymer matrix. Such behavior is characteristic of conductive polymer composites where electrical transport is governed by filler dispersion, interparticle contact, and polymer–particle interfacial compatibility rather than the insulating polymer matrix itself [21].

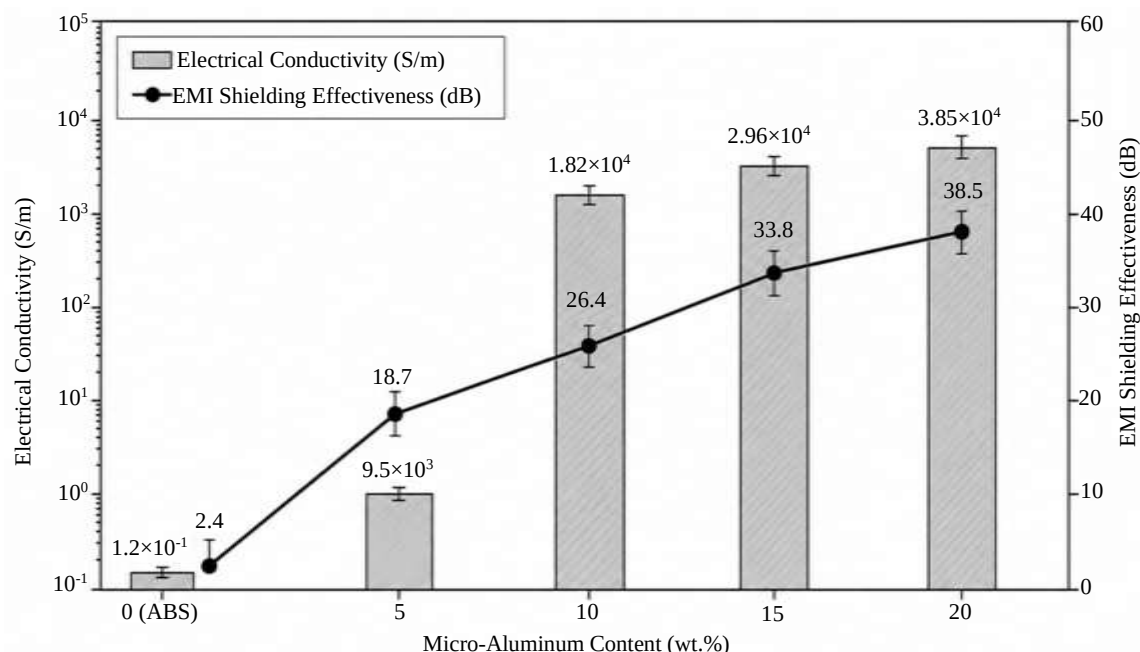


Figure 5. Electrical conductivity and EMI shielding effectiveness of micro-aluminum reinforced conductive polymer composites as a function of micro-aluminum content.

The improvement in electrical conductivity directly contributed to enhanced EMI shielding performance. The interconnected aluminum network effectively reflected, absorbed, and dissipated incident electromagnetic radiation, thereby reducing electromagnetic wave transmission through the composite. Increasing micro-aluminum loading resulted in higher shielding effectiveness because of the increased density of conductive pathways available for electromagnetic attenuation. The ABS-Al20 composite exhibited the highest EMI shielding effectiveness of approximately 38 dB, demonstrating its suitability for lightweight antenna housing applications where protection against electromagnetic interference is essential.

From a polymer composite perspective, uniform dispersion of the conductive filler was critical for simultaneously achieving high conductivity and mechanical reliability. The twin-screw extrusion process and silane surface treatment minimized particle agglomeration and promoted strong polymer–particle interfacial bonding, enabling the formation of stable conductive networks without compromising structural integrity. Consequently, the fabricated composites successfully combined lightweight construction, electrical conductivity, and EMI shielding within a single multifunctional material system. These characteristics make the developed micro-aluminum reinforced polymer composites highly promising for IoT-enabled antenna housings requiring reliable electromagnetic protection and long-term structural performance.

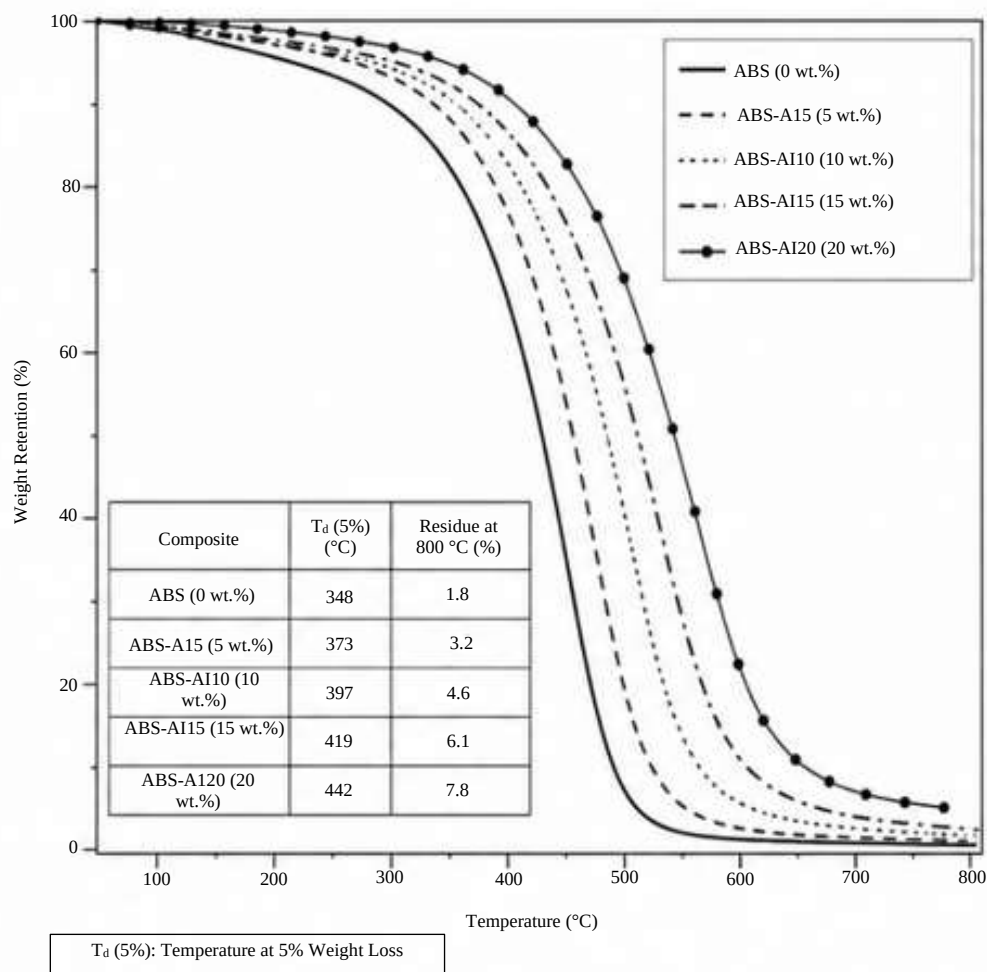
Thermal Stability and IoT-Based Performance Monitoring

The thermal stability of conductive polymer composites is a key requirement for lightweight antenna housings operating under varying service conditions. Figure 6(a) presents the thermogravimetric analysis (TGA) curves of the fabricated ABS/micro-aluminum composites. Compared with neat ABS, the incorporation of micro-aluminum particles shifted the degradation profile toward higher temperatures, indicating improved thermal resistance. The conductive filler acted as a thermal barrier by restricting polymer chain mobility and promoting more uniform heat distribution throughout the matrix [22].

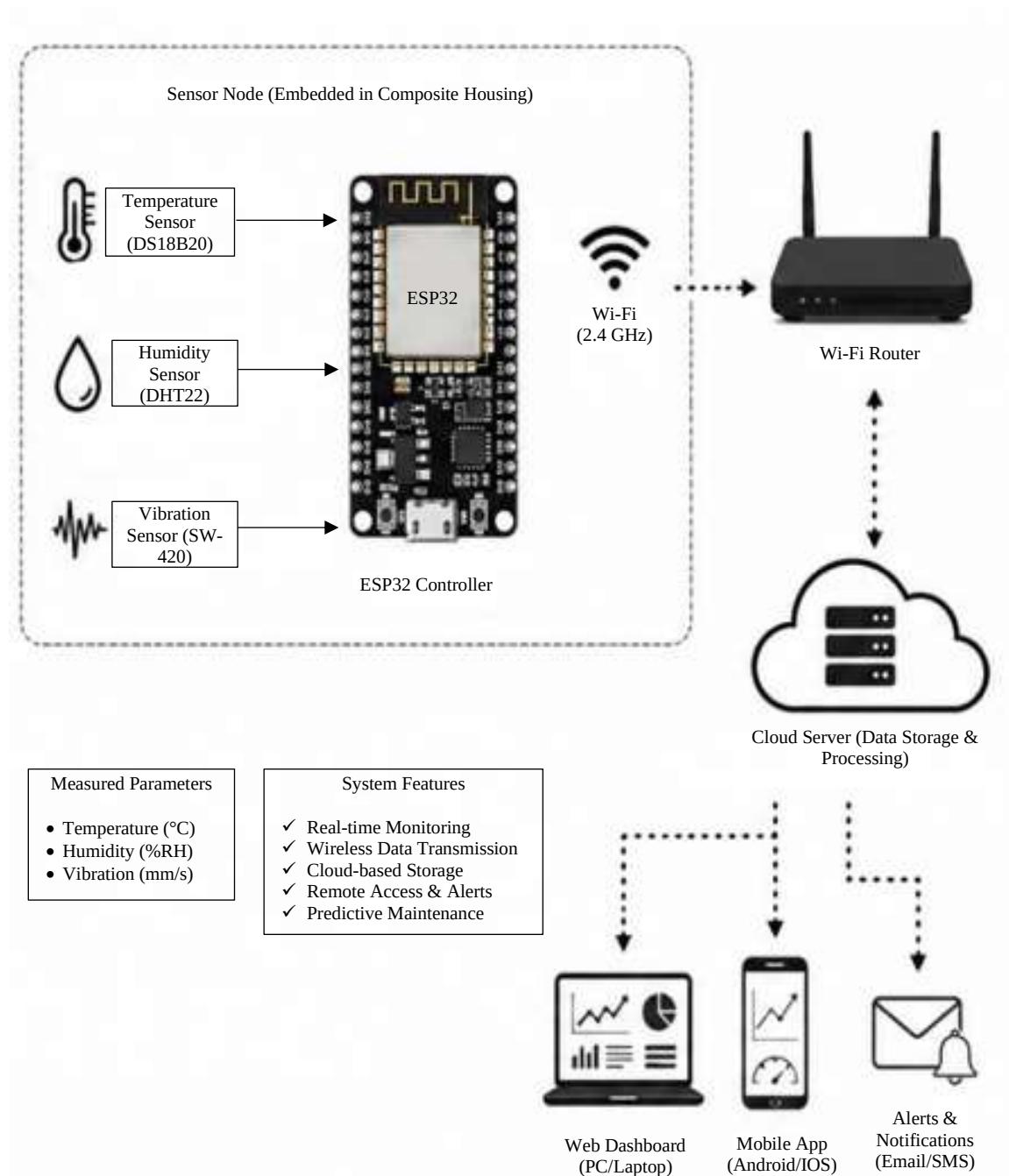
Among all formulations, the ABS-AI20 composite exhibited the highest thermal stability and residual mass, confirming that homogeneous filler dispersion and strong polymer–particle interfacial bonding effectively enhanced the thermal durability of the conductive polymer composite.

The improved thermal resistance is particularly beneficial for antenna housing applications, where elevated operating temperatures can adversely affect both structural integrity and electrical performance. The formation of stable conductive networks within the polymer matrix enables the composite to retain its electrical conductivity and electromagnetic interference (EMI) shielding capability even under prolonged thermal exposure. These results demonstrate that optimized micro-aluminum reinforcement provides a multifunctional polymer composite possessing lightweight characteristics, improved thermal stability, and reliable electrical performance.

The real-time monitoring capability of the developed antenna housing is illustrated in Figure 6(b). An ESP32-based IoT architecture was integrated with temperature, humidity, and vibration sensors to continuously monitor the operational condition of the conductive polymer composite. The acquired sensor data were transmitted wirelessly through a Wi-Fi gateway to a cloud server, enabling real-time visualization, storage, and remote access via a web dashboard or mobile interface. This intelligent monitoring framework facilitates continuous structural health assessment and early detection of abnormal operating conditions, thereby improving system reliability and reducing maintenance requirements [23].



(a)



(b)

Figure 6. Integrated thermal stability and IoT-based performance monitoring of electrically conductive micro-aluminum reinforced polymer composites showing (a) thermogravimetric (TGA) degradation curves and (b) IoT-Based Wireless monitoring architecture.

CONCLUSION

Electrically conductive polymer composites have emerged as multifunctional engineering materials that integrate lightweight structural performance with electrical conductivity, thermal stability, and electromagnetic interference (EMI) shielding. In this study, micro-aluminum reinforced ABS polymer composites were successfully fabricated and evaluated for IoT-enabled lightweight antenna housing applications. The developed composites demonstrated improved mechanical, electrical, thermal, and intelligent monitoring capabilities, highlighting their potential as next-generation multifunctional

polymer composite materials.

- *Enhanced Mechanical Performance:* The incorporation of micro-aluminum particles significantly improved the tensile and flexural strengths of the ABS matrix due to effective polymer–particle interfacial bonding and efficient stress transfer.
- *Improved Electrical Conductivity:* Formation of continuous conductive pathways increased the electrical conductivity with increasing micro-aluminum content, achieving a maximum conductivity of approximately 3.85×10^4 S/m for the ABS-Al20 composite.
- *Superior EMI Shielding:* The interconnected conductive network effectively attenuated electromagnetic radiation, providing an EMI shielding effectiveness of approximately 38 dB, making the composite suitable for antenna housing applications.
- *Enhanced Thermal Stability:* Thermogravimetric analysis confirmed that micro-aluminum reinforcement increased the degradation temperature and thermal resistance of the polymer composites, improving service reliability under elevated operating temperatures.
- *Successful IoT Integration:* The ESP32-based wireless monitoring system enabled real-time measurement of temperature, humidity, and vibration, with cloud-based data transmission for continuous structural health monitoring.
- *Multifunctional Polymer Composite:* The proposed ABS-Al20 composite successfully combined lightweight construction, mechanical strength, electrical conductivity, EMI shielding, thermal stability, and IoT-enabled monitoring within a single material system.

REFERENCES

1. Anis A, Elnour AY, Alam MA, Al-Zahrani SM, AlFayez F, Bashir Z. Aluminum-filled amorphous-PET, a composite showing simultaneous increase in modulus and impact resistance. *Polymers*. 2020;12(9):2038.
2. Wang X, Li L, Liu S, Nie Z, Wang W, et al. Partially fluorinated metallic surface constructing robust, thermally conductive and electrically insulating polymer composite. *Compos Sci Technol*. 2023 Oct 20;243:110225. doi: doi.org.
3. Kim D, Park K, Kim K, Cho S, Hirayama Y, Takagi K, et al. Cold compaction behavior of nano and micro aluminum powder under high pressure. *Compos Res*. 2019;32(3):141–7.
4. Vadivelu MA, Kumar CR, Joshi GM. Polymer composites for thermal management: A review. *Compos Interfaces*. 2016;23(9):847–72.
5. Megahed M, Fathy A, Morsy D, Shehata F. Mechanical performance of glass/epoxy composites enhanced by micro-and nanosized aluminum particles. *J Ind Text*. 2021;51(1):68–92.
6. Choi S, Im H, Kim J. Flexible and high thermal conductivity thin films based on polymer: Aminated multi-walled carbon nanotubes/micro-aluminum nitride hybrid composites. *Compos Part A Appl Sci Manuf*. 2012;43(11):1860–8.
7. Bao L, Zhang W, Zhang X, Chen Y, Chen S, et al. Impact of MWCNT/Al on the combustion behavior of hydroxyl ammonium nitrate (HAN)-based electrically controlled solid propellant. *Combust Flame*. 2020 Aug 1;218:218–228.
8. Wei B, Yang S. Polymer composites with expanded graphite network with superior thermal conductivity and electromagnetic interference shielding performance. *Chem Eng J*. 2021 Jan 15;404:126437.
9. Gao J, Xiong H, Han X, An F, Chen T. Synergistic effect of aluminum nitride and carbon nanotube-reinforced silicon rubber nanocomposites. *Molecules*. 2024;29(12):2864.
10. Choi S, Kim J. Thermal conductivity of epoxy composites with a binary-particle system of aluminum oxide and aluminum nitride fillers. *Compos Part B Eng*. 2013 Aug 1;51:140–147.
11. Yu J, Bang J, Jin Y, et al. Design strategies for thermally conductive polymer composites based on interface and network engineering. *Polym Compos*. 2026.
12. Veeranaath V, Sahu RK, Priya IM. Experimental and computational studies on characteristics of indigenously produced novel Aegle marmelos micro polymer reinforced aluminum composites using powder metallurgy. *J Mech Sci Technol*. 2025;39(2):587–610.
13. Jasim KA, Fadhil RN. The effects of micro aluminum fillers in epoxy resin on the thermal conductivity. *J Phys Conf Ser*. 2018;1003(1):012082.

14. Moosa MH, Shewakh WM, Ibrahim RA, Abu-Okail M, Farouk WM. Effect of innovative hybrid nano additives of Al₂O₃-MWCNT-SiO₂ on microstructural and tribological characteristics of carbon fiber-reinforced polymers for enhanced brake pad safety. *J Mech Sci Technol*. 2026;40(2):1069–80.
15. Ouyang Y, Hou G, Bai L, Li B, Yuan F. Constructing continuous networks by branched alumina for enhanced thermal conductivity of polymer composites. *Compos Sci Technol*. 2018 Sep 8;165:307–313.
16. Mishra P, Nazir T, Sarathi R, Paul M, Mondal M. Investigating thermal properties of electron beam irradiated silicone rubber/ATH/BN nano-micro hybrid composites. In: 2024 IEEE International Conference on High Voltage Engineering and Applications (ICHVE). 2024 Aug 18. p. 1–4. IEEE.
17. Wu H, Chiang S, Han W, Tang Y, Kang F, Yang C. Surface iodination: A simple and efficient protocol to improve the isotropically thermal conductivity of silver-epoxy pastes. *Compos Sci Technol*. 2014 Jul 30;99:109–116.
18. Mi YN, Liang G, Gu A, Zhao F, Yuan L. Thermally conductive aluminum nitride-multiwalled carbon nanotube/cyanate ester composites with high flame retardancy and low dielectric loss. *Ind Eng Chem Res*. 2013;52(9):3342–53.
19. Du FP, Li JJ, Fu P, Wu YG, Liao GY, Zhang YF, et al. Enhanced thermal conductivity of poly(L-lactide) composites with synergistic effect of aluminum nitride and modified multi-walled carbon nanotubes. *Fullerenes Nanotubes Carbon Nanostruct*. 2016;24(10):667–73.
20. Yu C, Zhang J, Li Z, Tian W, Wang L, et al. Enhanced through-plane thermal conductivity of boron nitride/epoxy composites. *Compos Part A Appl Sci Manuf*. 2017 Jul 1;98:25–31.
21. Nazir MT, Khalid A, Phung BT, Das AK, Cheetham P, Paramane A, et al. Electrical tracking, erosion and fire retardancy performance of silicone rubber insulation containing aluminum trihydrate, graphene and glass fiber additives. *CSEE J Power Energy Syst*. 2023;9(5):1918–25.
22. Yan W, Song X, Wang Y. Micro-aluminum simultaneously coated with metallic Cu, Ni, and Co nanoparticles: Thermal reaction and catalytic mechanism. *Coatings*. 2026 Jan 6;16(1):65.
23. Cao JP, Zhao J, Zhao X, You F, Yu H, et al. High thermal conductivity and high electrical resistivity of poly(vinylidene fluoride)/polystyrene blends by controlling the localization of hybrid fillers. *Compos Sci Technol*. 2013 Dec 13;89:142–148.