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Development of Conductive Polymer-Based Materials for Flexible Integrated Electronic Applications

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Abstract

As electronic devices become more common, EMI is turning into a bigger issue. Conductive polymer composites are considered promising because they are lightweight, resistant to corrosion, easy to shape, and stable. Adding conductive fillers such as graphene, MXene, carbon fibers, or certain metals can further improve their ability to block EMI and conduct heat and electricity. These materials are very thin, but they can block sounds louder than 80 dB. 3D printing and template fabrication are two new ways of making things that allow you to create strong and flexible conductive networks with little filler. However, there are still some issues that need to be addressed, such as how to distribute the filler evenly, control the microstructure, and keep the polymer-filler interface dense. Some proposed improvements are to modify the interface, mix different types of fillers, and build structures that are porous or have more than one layer. If designed and manufactured correctly, these conductive polymer composites can be used in flexible electronics, wearable devices, and next-generation thermal management systems

1. INTRODUCTION

The demand for flexible and integrated electronic devices in Indonesia is rapidly increasing, in line with the growth of the national electronics industry, which reached 8.5% in 2023 according to the Central Bureau of Statistics (BPS) (M. A. Shahid et al., 2025). However, most conventional electronic devices still use rigid inorganic materials, which limit innovation in wearable devices, flexible sensors, and foldable electronics. There is an urgent need for new materials that can support the national digital transformation and the growth of Industry 4.0. These materials should be flexible and highly conductive. Finding new materials that can help the country go digital and support the growth of Industry 4.0 is very important. These materials must be able to bend and conduct electricity (Ali et al., 2025). In the era of rapid technological development, integrated flexible electronics have gained attention, particularly for applications such as portable devices and communication systems. Related books and

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articles can provide insights into how the development of this material aligns with global market trends in integrated electronics (Xia & Shi, 2024).

Globally, research on conductive polymer materials has advanced rapidly, focusing on improving performance, stability, and compatibility with fabrication processes. In Indonesia, many studies are still focused on the synthesis and basic characterization stages, while applications in flexible electronic devices are still very limited (Tawsif et al., 2025). Mechanical engineering relies on materials science to select and process materials for creating highly reliable, efficient, and cost-effective mechanical components and systems. In today's sectors, particularly electronics and communications, choosing the right materials is crucial. Conductive polymers, which combine the qualities of polymers with their ability to conduct electricity, have opened up numerous new possibilities for creating electrical systems that are lighter and more flexible (Ir. Zufri Hasrudy Siregar, S.T., M.Eng., 2025). According to the research's red map, developed countries have incorporated conductive polymers into various applications. This includes biomedical sensors, flexible displays, and renewable energy devices. Research in Indonesia is still limited to material development and has not extensively addressed integration aspects into electronic devices (Ahmad et al., 2025).

Conductive polymers, which have high conductivity and extremely high mechanical stability, are very suitable for highly flexible electronic applications in Indonesia. There hasn't been a lot of investigation into how these materials can work with mass-produced integrated electronic systems. This study looks into conductive polymer materials that are made up of more than one substance and are good for a wide range of electronic uses. These materials may also be directly added to electronic devices. This study also suggests a new way to make things that is good for the environment and may be used by businesses in the country (A. Shahid et al., 2025). For example, in the context of engineering economics, new technologies involving conductive polymers need to be analyzed from a cost-benefit perspective. Decision-making in the development of this material involves calculating investments that can increase added value for the industry, as well as the potential for long-term financial gains. Therefore, it is important to use the basic principles of engineering economics, which include cost, benefit, and risk analysis of developed technological applications (Siregar et al., 2024). This book shows examples of material progress, like lightweight alloys in the automotive and aerospace industries. This example can be used to show how flexible conductive polymer materials can affect electronics, drawing parallels from the need for high-performance materials in that field (Zhao et al., 2024).

Recent global research over the past three years has shown very significant progress in the field of modifying the structure of conductive polymers. The main focus of these studies is to improve several important properties of conductive polymers, such as electrical conductivity, thermal stability, and the ability to adapt and work optimally with flexible substrates. Researchers continue to work on creating materials that not only have high electrical conductivity but can also withstand high temperatures (Khan et al., 2023). They are also ensuring that their mechanical properties allow them to function well on various flexible surfaces. Therefore, by developing conductive polymer materials for flexible and integrated electronic applications, this research is expected to make a significant contribution to the development of material technology in Indonesia and simultaneously drive the country's electronics industry to become independent (Abidin et al., 2025).

As a result, this research is expected to aid in the development of technically superior functional materials based on conductive polymers that meet the needs of the national industry. The results of this study are also expected to reduce dependence on imported materials and promote technological independence in the flexible electronics industry in Indonesia.

2. METHODS

This research uses an approach with the following main stages: synthesis of conductive polymer composites, characterization of material properties, prototyping, and performance testing.

1. Synthesis of Conductive Polymer Composites
    - Material Options: Polymer matrices (such as TPU, PU, PVP, or PET) combined with conductive fillers like graphene, silver nanowires (AgNW), carbon nanotubes (CNT), or hybrid combinations.
    - Synthesis methods: include physical mixing (solution stirring, combining, hot pressing, blade coating, spray coating), and laser treatment for integrating or forming fillers onto polymer substrates, in-situ reduction or sintering of conductive networks (Xu & Gu, 2025).
2. Material Property Characterization

- Structural and Morphological Identification: use SEM, TEM, XRD, and UV-Vis techniques to identify the dispersion and network structure of the filler (Ahmed et al., 2025).

3. Prototype Fabrication
    - Prototype Fabrication: The process of creating flexible films, electrodes, sensors, or electronic devices using printing techniques (stamping), laser dyeing, or 3D printing. Electrical and thermal conductivity measurements can be performed by measuring layer voltage, resistivity, and thermal conductivity. Mechanical stability testing can also be done by measuring impact, stretching, and fatigue (Olamide et al., 2025).
4. Performance Testing
    - Performance Testing: Sensor sensitivity testing, cycle stability, thermal response (Joule heating), EMI shielding, and application in flexible devices.
    - Application Evaluation: Testing on real-world applications such as strain sensors, flexible electrodes, thermal devices, and wearable electronics (Liu et al., 2024).

Table 1. List of Materials and Their Functions

Main Material	Functions in Research	Usage Example
Polyaniline (PANI)	Main Conductive Polymer	Sensor, electrode
Polypyrrole (Ppy)	Main Conductive Polymer	Sensor, supercapacitor
PEDOT:PSS	Main Conductive Polymer	Flexible film,electrode
Graphene/Ag Nanowire	Nanofillers for Composites	Increasing Conductivity
PVA, PEO	Flexible polymer matrix	Improving flexibility

Table 2. Example of Characterization Test Result Data

Conductivity (S/cm)	Flexibility (Bending Cycles)	Environmental Stability (Days)
PANI/Graphene	120	10.000
PEDOT:PSS	80	8.000
PPy/PVA	60	7.500

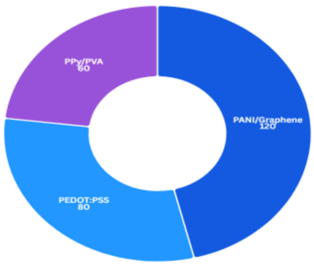

Fig.1. Data from Characterization Test Results

Source: Data taken from Micromachines 2022(Pascual et al., 2022)

Table 3: Number of Publications Related to Conductive Polymers (2010–2023)

YEAR	Number of publication
2010	2.183
2015	8.000
2020	15.000
2023	19.852

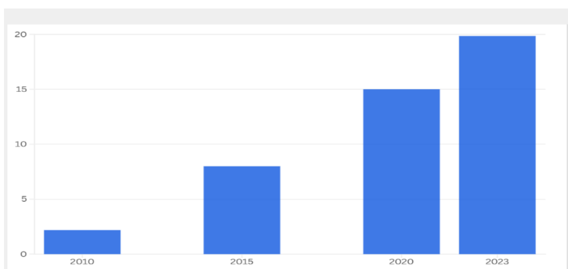

Fig. 2. Number of Publications Related to Conductive Polymers (2010–2023)

Source: Data taken from the total number of publications related to conductive polymers (2010–2023) (Wang et al., 2025)

Method Explanation

1. Material Synthesis: Conductive polymers such as PANI, PPy, and PEDOT:PSS are synthesized by in situ polymerization or by incorporating nanofillers (such as graphene or gold nanowires) to enhance conductivity and flexibility.
2. Characterization: The material was tested using XRD, FTIR, and SEM, as well as conductivity and mechanical (bending) tests to assess its physical and electrical performance.
3. Device Fabrication: Conductive polymer films were fabricated using the spin coating technique.

Table 4: Data on Flexible Conductive Polymer Materials

Composite Material	Electrical Conductivity(s/cm)	Thermal Conductivity	EMI Shielding Effectiveness(dB)	Thickness (mm)	Strain (%)
Silicon Polymer (Liquid Metal)	-	3.46	63.19(X-band,300% strain)	-	300
PI (Polyimide, Mxene)	-	3.49	85	-	-
EMA(Ethylene Methyl Acrylate)	0.01	1.3	32.4	-	-
PDMS/Ppy(polydimethylsiloxane,Polpyrrole)	24.03	-	21 (0,5 mm,X-band)	0.5	-
TPU/Long CNT (Thermopastic Polyurethane,CNT)	0.0019	0.51	42.5	-	-
Mxene-PANI-(Mxene,polyaniline Copolymer)	7.813	0.687	45.18(8.2 G Hz)	-	-
TPU?Graphene(Ultra-thin, 50, μm	0.303(mS/m)	22.4	57(10 G Hz)	0.05	-

3. RESULT AND DISCUSSION

This section talks about the results of testing and analyzing the performance of different conductive polymer composite materials based on the data that has been presented, and it also compares these results to those found in the most recent literature.

Electrical and Thermal Conductivity

Combining conductive fillers such as carbon nanotubes (CNT), graphene, MXene, and liquid metals shows improved electrical and thermal conductivity. For example, a liquid metal/silicon polymer composite has a thermal conductivity of 3.46 W/mK and can still bend up to 300% strain. On the other hand, the ultra-thin TPU/AgNW/Graphene has a thermal conductivity of 22.4 W/mK, but its electrical conductivity is only 0.303 mS/cm. It has been proven that adding fillers like MXene and Fe_3O_4 to a polymer matrix increases both electrical and thermal conductivity at the same time(Choudhary et al., 2022).

Effectiveness of EMI Shielding

The effectiveness of EMI shielding (EMI SE) is highly influenced by the type of filler, the structure of the conductive network, and the material thickness. Composites with hybrid networks (e.g., graphene-silver nanowires on TPU) can achieve EMI SE of up to 57 dB at a thickness of only 0.05 mm, far exceeding many conventional materials.Liquid metal/silicon polymer-based composites also show high EMI SE (63.19 dB at X-band, 300% strain), which is due to the formation of conductive paths caused by the deformation of liquid metal particles. Other studies confirm that increasing the filler content and material thickness generally enhances EMI SE; however, the primary mechanism may shift from reflection to absorption as structure and composition change (Jovanović et al., 2023)

Influence of Strain and Flexibility

Some composites, such as LM/silicon polymer, still maintain high EMI shielding and thermal conductivity even under significant stress. This makes them very useful for flexible applications. Meanwhile, CNT and carbon black-based composites also exhibit resistance sensitivity to strain, which is beneficial for strain sensor applications (Parvini, 2025).

Comparison with Literature

This result aligns with the literature emphasizing the importance of conductive network design, filler selection, and microstructure control to optimize conductivity and EMI shielding in polymer composites. The use of hybrid fillers and innovative fabrication techniques (e.g., blade-coating, filler orientation, or foam structure) has been shown to significantly improve the performance of multifunctional materials (Zhang, 2024).

Table 5. Summary of Research Methods

2022 period	Examples of Key Techniques/Materials
Composite Synthesis	Solution mixing, blending,hot-pressing,laser processing,AgNW,CNT,graphene
Characterization	SEM, TEM, XRD, UV-Vis, electrical and thermal conductivity measurements, mechanical testing
Prototype Fabrication	Printing,laser patterning,3D printing,Wetting-dewetting,gravure printing
Performance Testing	Sensor testing, EMI shielding, Joule heating, stability

4. CONCLUSION

The design of a three-dimensional (3D) network of conductive fillers such as graphene, MXene, expanded graphite, or a combination with metals (e.g., Ag nanowire) within a polymer matrix significantly enhances thermal conductivity and EMI shielding effectiveness, particularly when supported by fabrication methods such as pre-melt blending, powder mixing, or thermal molding, which create a continuous conductive network and reduce interfacial resistance. Hybridizing one-dimensional fillers (Ag nanowire) and two-dimensional fillers (graphene, MXene), as well as controlling the orientation of the fillers using techniques like blade-coating or external alignment, creates ultra-thin films with very high conductivity and EMI shielding, as well as good flexibility for flexible electronic applications. Taguchi-TOPSIS and other approaches have been demonstrated to work well for identifying the optimal matrix-filler ratio and process parameters for the greatest multifunctional performance. Functionalizing the surfaces of fillers (such silane and surfactant) and engineering the interface makes the composite perform better by improving dispersion, compatibility, and heat/electric transmission. Additionally, the implementation of multilayer or porous structures in composites enhances conductive pathways, improves EMI absorption mechanisms, and preserves the material's flexibility and mechanical strength.Combining 3D network design, hybridization, and orientation of fillers, optimizing composition, engineering interfaces, and developing multilayer/porous structures in a way that works together has been shown to greatly improve the thermal conductivity, EMI shielding, and mechanical performance of conductive polymer composites for advanced electronic applications.

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