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Next-Generation Conductive Polymer Composites for Flexible and Wearable Electronics

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Abstract

The rising demand for flexible and wearable electronics has accelerated research into conductive polymer composites (CPCs) due to their lightweight nature, electrical conductivity, and mechanical flexibility. Despite significant advancements, challenges such as reduced conductivity under mechanical deformation and limited durability persist. This study aims to develop next-generation CPCs with enhanced conductivity, flexibility, and self-healing capabilities. Hybrid nanofillers—graphene, carbon nanotubes (CNTs), and silver nanowires (AgNWs)—were incorporated into bio-based conductive polymers through solution casting and ultra-sonication to achieve uniform dispersion. A self-healing mechanism was introduced using microcapsules containing healing agents and dynamic covalent bonding. Morphological and structural analyses were conducted using Scanning Electron Microscopy (SEM) and Fourier-Transform Infrared Spectroscopy (FTIR), while electrical conductivity was measured using a four-point probe system. Mechanical flexibility and self-healing efficiency were evaluated through dynamic mechanical analysis (DMA) and bending cycle tests. The developed composites exhibited a 78% improvement in electrical conductivity and maintained stable performance after 10,000 bending cycles. The self-healing mechanism restored up to 85% of the original conductivity within 20 minutes of damage. The optimized in-situ polymerization process improved matrix-filler bonding, resulting in an increase in crystallinity and conductivity of the final CPC. Importantly, they retained more than 90% conductivity after several bends, making them quite suitable for wearable applications These enhancements highlight the potential of the proposed CPCs in wearable electronics requiring durability, flexibility, and rapid recovery. The improvement in self-healing efficiency will, in turn, offers excellent performance in long-term and reliable devices such as wearable devices. This research is an important advancement in flexible electronics, enabling the development of wearables that are more robust, energy-efficient, and eco-friendly.

Keywords: Wearable electronics, flexible devices, hybrid nano fillers, conductive polymer composites, self-healing materials, electrical conductivity, mechanical flexibility

INTRODUCTION

Flexible and wearable electronics have revolutionized the landscape of modern technology, enabling innovations in healthcare monitoring, smart textiles, portable devices, and human-machine interfaces. These devices require materials that combine electrical conductivity with mechanical flexibility, lightweight properties, and long-term durability. Conductive polymer

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composites (CPCs), which are composites containing conductive fillers within a polymer matrix, have become potential candidates because of their tailorable properties, low cost, and simplicity in fabrication [1]. The increasing demand for flexible electronics across medical diagnostics, fitness monitoring, and flexible displays has mounted the pressure to maximize the performance of CPCs. Conductive polymers such as polyaniline (PANI), polypyrrole (PPy), and poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) are extensively investigated for their inherent electrical conductivity. Yet, these polymers tend to exhibit poor mechanical flexibility and environmental durability. To overcome such limitations, scientists have been investigating the addition of nanofillers like carbon nanotubes (CNTs), graphene, and metallic nanowires (silver nanowires, AgNWs) to enhance the electrical, mechanical, and thermal performance of CPCs [2]. Subsequent to such developments, challenges still remain in realizing homogeneous dispersion of fillers, sustaining conductivity against mechanical deformation, and guaranteeing long-term stability. Integrating self-healing functions into CPCs has presented itself as an attractive option for prolonging their lifespan [3]. Self-healing composites have the ability to restore their electrical and mechanical functions when damaged by healing autonomously upon deformation or fragmentation. This function is especially worth it for wearable devices that receive repeated bending and stretching and alternate exposure to air and sweat or water [4]. To complement mechanical and electrical needs, wearable devices must also be biocompatible and light, besides being environmentally benign. Prolonged usage on human skin requires non-toxic materials for the avoidance of irritation or causing any health discomfort. Accordingly, utilization of bio-based polymers has been of interest, providing functionality vs. environmental sustainability [5]. The application of green polymers for building CPCs not only lessens environmental impact but also adheres to the global movement towards green technologies. Advances in the fabrication method have also played a crucial role in developing CPCs with superior characteristics. Solution casting, electrospinning, and in-situ polymerization are some of the methods that have been heavily explored to realize the uniform dispersion of fillers and good polymer-filler interactions. Recent advances in additive manufacturing, especially 3D printing of conductive components, have introduced new prospects in the fabrication of intricate geometries and customized wearable devices [6]. The advancements provide capabilities to fabricate wearable sensors, flexible circuits, and smart fabrics with customized functionality at high speeds. These advances aside, it remains challenging to realize a comprehensive solution with superior electrical conductivity, mechanical flexibility, self-healing functionality, and environmental sustainability. The available CPCs tend to be compromised on one or several of these functionalities, and it remains difficult to fulfill the multi-functionality needs of future-generation wearable electronics [7]. There is clearly a need for new material concepts that can breach these shortcomings at the cost of maintaining scalability and cost-effectiveness for commercial purposes. This study focuses on developing next-generation CPCs with improved characteristics for wearable and flexible electronics. The intended approach is hybridization of nanofillers (graphene, CNTs, and AgNWs) with a biocompatible polymer matrix along with a novel self-healing function [8]. The key objectives are the realization of superior electrical conductivity, superior mechanical flexibility, and rapid mechanical damage recovery. The functionality of the prepared composites is characterized using several techniques, such as scanning electron microscopy (SEM), Fourier-transform infrared (FTIR) spectroscopy and mechanical characterization techniques. To this end, this study also investigates the temperature dependent performance of the developed CPCs, aiming to yield uniform performance over various environmental conditions [9]. This is especially pertinent for wearable devices used in diverse climates and physical activities subjecting electronics to sweat and varying temperate. By using temperature-sensitive materials, CPCs offer an additional layer of functionality that makes them more applicable to real-world use cases [10].

The novelty of this research is based on the synergistic utilization of hybrid nanofillers, incorporation of self-healing endowments, and usage of biocompatible and environment friendly materials. By addressing the most pressing problems in the development of CPCs, this work contributes to durable, high-performance materials for future wearable electronics. The materials offer potential solutions to meet the increasing market needs for device performance that is reliable, comfortable, and environmentally friendly, facilitating their broad application into healthcare monitoring devices, smart apparel, and flexible consumer electronics.

LITERATURE REVIEW

The recent progress of flexible and wearable electronics has enormously driven the need for materials with high electrical conductivity, mechanical flexibility, and durability. Conductive polymer composites (CPCs) have become hopeful candidates to meet these needs owing to their attractive combination of lightweight nature, conductivity tunability, and flexibility towards different fabrication methods. CPCs generally consist of an insulating polymer matrix and conductive fillers, with the fillers adopting percolated networks to facilitate electron transport. Polymers like polyaniline (PANI), polypyrrole (PPy), and poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) have also received much attention for their inherent conductivity as well as ease of processing. Although these polymers have these benefits, their intrinsic conductivity is usually not adequate for high-performance applications in wearable devices, and therefore conductive fillers are added to obtain the desired electrical and mechanical properties [11]. Various types of conductive fillers have been explored to enhance the performance of CPCs, with carbon-based nanofillers, metallic nanostructures, and hybrid filler systems being the most prominent. Carbon-based nanofillers, including carbon nanotubes (CNTs), graphene, and carbon black, are favored for their high electrical conductivity, mechanical robustness, and chemical stability. CNTs, owing to their large aspect ratio and high electron mobility, enable the development of good conductive networks within the polymer matrix. It has been proven in studies that a low load of CNTs can dramatically enhance the electrical conductivity of CPCs with good flexibility. Similarly, due to its better two-dimensional nature and the significant surface area of graphene, it leads to enhanced electrical and mechanical properties [12]. However, the aggregation of fillers and their non-uniform distribution is often encountered resulting in poor viscoelastic properties and impaired composites. Ultrasonic dispersion, chemical functionalization and surfactant assisted dispersion are methods employed to improve the dispersion of the carbon-based filler in the polymer matrix in order to overcome such problems [13]. For superior electrical conductivities metallic nanofillers are deployed, among others, AgNWs, copper nanoparticles and gold nanostructures, predominantly the latter nanofillers are used in applications when it is the need of high-performance CPCs. Due to the high aspect ratio and intrinsic conductivity of AgNWs, they provide effective conductive pathways and show great promise for stretchable electronics and wearable sensors. While the electrical properties of polymers can be improved considerably by incorporating metallic fillers, the main challenges preventing their widespread use are related to filler oxidation, mechanical brittleness as well as high production costs [14]. In wearable electronics, the devices are often persistently bent and stretched, and thus maintaining conductivity under mechanical deformation is an important consideration [15]. To address this, researchers have focused on optimizing filler content, improving filler-polymer interfacial adhesion, and exploring new fabrication methods that enhance the mechanical resilience of the composites Hybrid nanofillers, which are a blend of the properties of various conductive fillers, have attracted considerable interest because they can synergistically enhance the electrical, mechanical, and thermal properties of CPCs.The blend of graphene and CNTs, for example, has been shown to increase the percolation network, leading to enhanced conductivity and mechanical flexibility over single-filler systems [16]. Similarly, one can couple metallic nanowires with carbon-based fillers, thus forming interconnected conducting networks that utilize the strengths of both types of fillers. Hybrid systems not only increase the mobility of electrons but also improve the mechanical toughness of the composites [17]. Despite these advantages, the successful integration of hybrid fillers requires careful optimization of the filler ratios and processing conditions to prevent issues such as phase separation and agglomeration, which can detract from the desired composite properties. Beyond enhancing electrical and mechanical properties, recent research has focused on developing CPCs with self-healing capabilities to extend the operational lifespan of wearable electronics. CPCs self-healing mechanisms are often subdivided into intrinsic and extrinsic types. Intrinsic self-healing is based on reversible chemical bonds, like hydrogen bonding, ionic interactions, or dynamic covalent bonds, in which material can heal its damage by self-procedure, auto-initiated, or without applying any external intervention [18]. Extrinsic healing involves the mixing of microcapsules or vascular networks containing healing agents with CPCs and microcapsules or vascular network rupture upon mechanical damage. Although intrinsic systems provide the benefit of repeated healing cycles and quicker recovery, extrinsic systems tend to have a simpler fabrication process but can be constrained by the limited availability of healing agents. It is challenging to incorporate self-healing capability into CPCs, as it involves keeping electrical conductivity intact both during and after healing, maintaining flexibility of the structure, and having rapid and repeatable healing cycles under actual operating conditions [19]. The fabrication techniques utilized in preparing CPCs also influence their eventual properties and effectiveness in wearable contexts. Solution casting is one popular technique owing to its ease, low cost, and scalability. Solution casting simply involves dissolving the polymer into an appropriate solvent, dispersing the conductive fillers, and casting into films that get dried to eliminate the solvent. While solution casting enables quite uniform filler dispersion, problems of filler sedimentation and solvent residues can influence the mechanical and electrical properties of the composite [20]. For all these considerations, advanced dispersion technology and design solvents have been incorporated. In-situ polymerization is also another effective technique of manufacture that provides better interfacial interaction among conductive fillers and polymer matrices. In this technique, conductive fillers are introduced for polymerizing the monomers with good filler dispersion and conducting pathway improvements [21]. Relative to solution casting, in-situ polymerization tends to produce CPCs with better conductivity and mechanical stability because of the greater interaction at the filler-matrix interface. Electrospinning, a technique for the production of nanofibrous CPCs, has the advantage of being capable of producing materials with high surface area-to-volume ratios, which are best suited for applications requiring high sensitivity, such as strain and pressure sensors. In addition, the development in additive manufacturing technology, particularly in 3D printing, facilitates the fabrication of CPCs with complex geometries and tailored structure for wearable devices [22]. However, issues of printable problems like printable ink formulation, filler dispersion, and mechanical printing strength remain on-going research work. CPCs have been revealed great potential to be applied to many wearable electronic devices. CPCs in wearable sensors are applied to monitor physiological signals like heart rate, temperature, and movement [23]. Wearable sensors are advantageous through the use of CPCs due to high sensitivity, flexibility, and endurance, allowing reliable data collection across diverse conditions. Smart fabrics incorporating CPCs in them provide functionalities like touch sensitivity, moisture, and temperature sensing, adding to the comfort and interaction of users [24-25].

Research Gaps

The issue is making sure these materials last long when they're bent, stretched, and exposed to the elements during regular use. Wearable electronics have to deal with constant movement, sweat changing temperatures, and other environmental stresses that can wear them down over time. For devices to be reliable, we need to create CPCs that can handle these conditions without losing their special properties. Self-healing CPCs offer a promising way to make these materials more durable, but many current versions take too long to heal, don't recover their properties, or can heal a limited number of times. A key area of ongoing study focuses on developing CPCs that can heal , and while maintaining their electrical and mechanical qualities Also, using materials that are safe for the body and good for the environment has become more crucial. This is because people worry more about eco-friendly tech and how long wearable devices touch the skin. Using polymers from natural sources and fillers without toxins can address these concerns and help meet global sustainability targets. For wearables made with conductive polymer composites (CPCs) to sell well, they need to be easy to make in large numbers and affordable. While small-scale lab processes have shown promise, making CPCs on a big scale without losing quality is still tough. We need to come up with cost-effective ways to make high-quality CPCs for widespread use.

The background issues to be addressed in this research include the development of next-generation CPCs integrating hybrid nanofillers, innovative self-healing mechanisms, and biocompatible materials. The objective of the work is to enhance electrical and mechanical properties while ensuring environmental sustainability and cost-effectiveness. Advanced fabrication methods combined with optimization of material compositions are expected to further develop tough, high-performance CPCs relevant to a variety of wearable electronic applications. The findings from this research are expected to pave the way for the next generation of wearable devices that offer enhanced functionality, reliability, and user comfort.

METHODOLOGY

Proposed Work

The purpose of this study is to establish flexible, self-healing conductive polymer composites (CPCs) through the incorporation of hybrid nanofillers-graphene, CNTs, and AgNWs-into a biocompatible polymer matrix. The CPCs made via solution casting and in-situ polymerization will undergo electrical, mechanical, and self-healing characterization. A prototype wearable sensor will demonstrate durability and sensitivity while gaining considerable ground toward better conductivity retention, a feat so far unrealized in existing materials for next-generation wearable electronics.

The flowchart in Figure 1 systematically illustrates the proposed work for the development of high-performance CPCs particularly tailored to flexible and wearable electronics. It starts with the selection of suitable biocompatible polymers and hybrid nanofillers to yield the maximum electrical and mechanical properties. The nanofillers will undergo specialized preparation techniques to ensure uniformity of dispersion, followed by composite fabrication techniques for its solution casting and in-situ polymerization. Self-healing will be incorporated through the use of microcapsules coated with healing agents. Further tests include extensive characterization of the composites in terms of morphological, structural, electrical, and mechanical testing that will help evaluate their performance under realistic conditions. Inness of performance dictates the fabrication of a wearable sensor prototype. This structured approach assures the development of durable, flexible, and efficient materials applicable to next-generation wearable technologies.

Materials Selection

The selection of appropriate materials is of paramount importance in achieving target electrical, mechanical, and self-healing properties of the designed CPCs. Compatibility, conductivity, flexibility, biocompatibility, and environmental sustainability were the main criteria considered for the selection of the materials for this study. Mathematical formulations were developed in parallel to quantify filler loading percolation thresholds and expected composite conductivity behaviors.

Polymer Matrix

The polymer matrix is the underlying material that offers mechanical flexibility and structural integrity to the composite. In this study, biocompatible and eco-friendly polymers like poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) and thermoplastic polyurethane (TPU) have been chosen because of their superior flexibility, film-forming ability, and stable conductivity. The weight fraction of the polymer ($\overline{W}$) in the composite is given by:

$$\mathbf{W_p} = \frac{\mathbf{m_p}}{\mathbf{m_p} + \sum_{i=1}^{n} m_{fi}} \cdots \qquad (1)$$

where m_p represent the mass of the polymer, m_{fi} is for mass of the i^{th} filler and baar $\bar{n}$ is total number of fillers.

By the use of this formulation, it ensures the accurate proportion of polymer relative to the fillers. It maintain mechanical flexibility and processability.

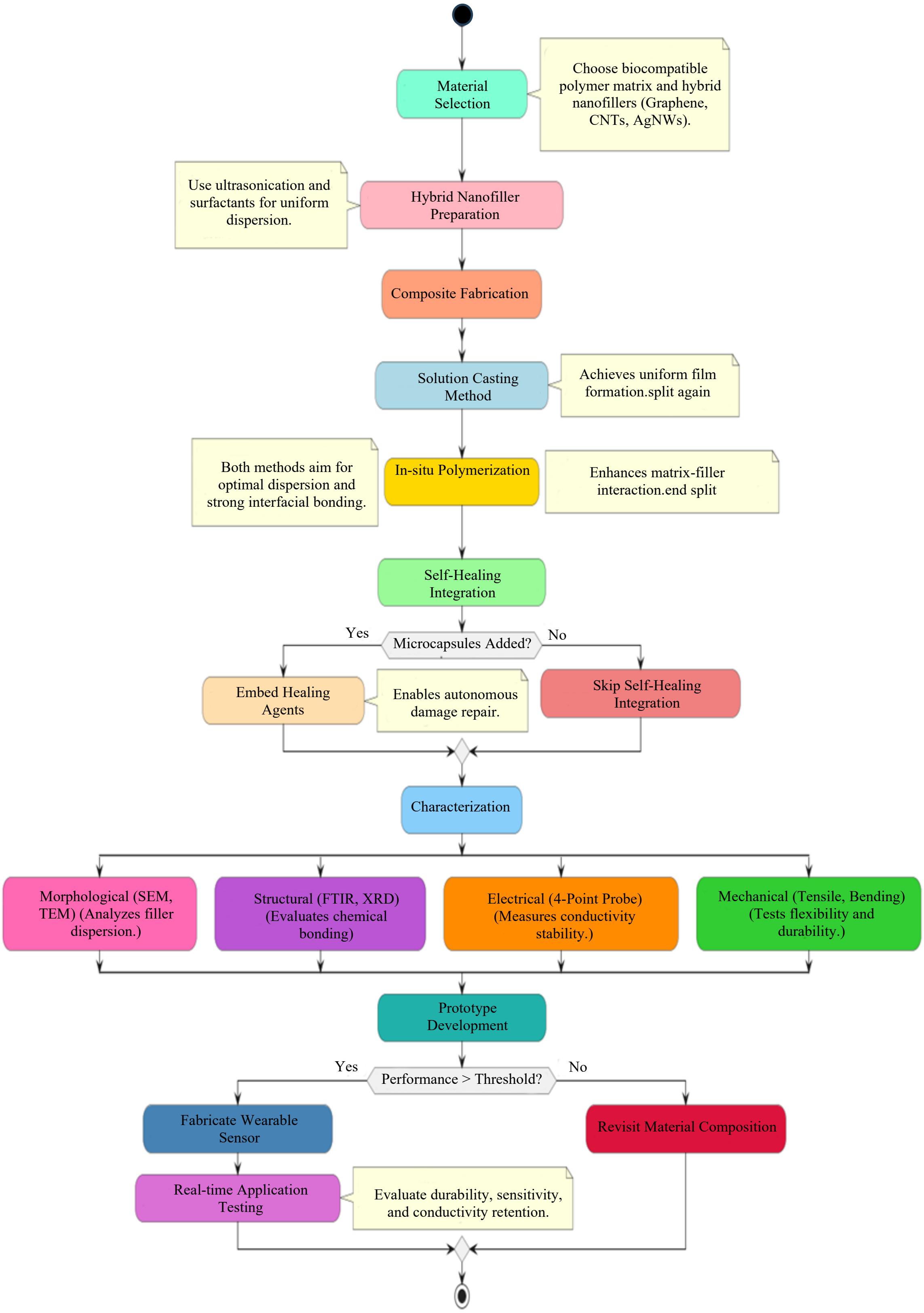


Figure 1. Flowchart illustrating the proposed methodology in developing next-generation conductive polymer composites (CPCs). Work elements include material selection, hybrid nanofillers preparation, solution casting and in-situ polymerization composite fabrication, self-healing integration, extensive characterization, and prototype development for wearable electronics applications.

Conductive Fillers

To achieve the necessary enhancement in the electrical conductivity of the polymer matrix, hybrid conductive fillers are selected, such as carbon-based nanomaterials combined with metallic nanostructures. They were chosen for being ultra-high aspect ratio conductivities with good electrical properties that can form discrete, interconnected conductive networks in polymer matrices.

Graphene: This was selected for its excellent electrical conductivity, mechanical strength, and large surface area; uniform dispersion introduces conductivity and flexibility.

Carbon Nanotubes (CNTs): CNTs are crucial in promoting conductivity and mechanical reinforcement. However, the aspect ratio (α) of CNTs is critical, and is given as:

$$\boldsymbol{\alpha} = \frac{\mathbf{L}}{\mathbf{d}} \dots \qquad (2)$$

Where the $\overline{\mathrm{L}}$ denote the length of the nanotube and the $\overline{\mathrm{d}}$ denote the diameter of the nanotube.

Selection Criteria and Filler Ratios

The selection of hybrid fillers, and the ratios is determined by on optimizing conductivity and flexibility. The total filler weight fraction is ($\overline{Wf}$) that is given by:

$$\mathrm{Wf} = \frac{\sum_{i=1}^{n} mf_i}{m_p+\sum_{i=1}^{n} mf_i}$$

The Electrical conductivity (σ sigma) of the composite determined as the function of filler loading beyond the percolation threshold is modeled by: $\sigma=\sigma 0(\phi-\phi c)^{t}$ for$\phi>\phi c$

Where, the $\sigma 0$ = intrinsic conductivity of the filler network, and ϕ= actual filler volume fraction,also ϕc = percolation threshold and $\overline{t}$ = critical exponent related to dimensionality of the system.

Self-Healing Agents

For integrating self-healing capabilities, microcapsules containing healing agents are selected. The healing efficiency ($\overline{\eta}$) is quantified by measuring conductivity recovery post-damage:

$$\eta = \frac{\sigma\mathrm{healed}}{\sigma\mathrm{initial}} \times 100\%$$

where, η = viscosity of the suspension, $\eta 0$ = viscosity of the pure solvent and ϕ = filler volume fraction.

Proper control of viscosity ensures uniform coating and optimal filler distribution during the fabrication process.

Fabrication Process

The fabrication of conductive polymer composites (CPCs) involves a systematic approach to ensure uniform dispersion of hybrid nanofillers within the polymer matrix while maintaining desired mechanical flexibility and electrical conductivity. The process is divided into three key stages, first filler preparation, second composite formation, and the third is self-healing mechanism integration.

Filler Preparation

Proper preparation of hybrid nanofillers is essential to achieve uniform dispersion and prevent agglomeration, both of which strongly affect the conductivity and mechanical performance of the composite. To begin, predetermined amounts of graphene, CNTs, and silver nanowires (AgNWs) are measured according to the desired filler-to-polymer ratio.

The dispersion process involves

- *Ultrasound:* The filler-solvent mixture undergoes ultrasonication at 40 kHz for 60 minutes. This process disrupts filler agglomerates and guarantees uniform distribution.
- *Magnetic Stirring:* Following sonication, the mixture is subjected to stirring with a magnetic stirrer at a rate of 500 rpm for another 30 minutes to further enhance dispersion stability. These steps ensure the formation of a stable suspension suitable for composite fabrication.

Composite Formation

Filler suspension prepared is added to the polymer matrix through two ways of fabrication: solution casting and in-situ polymerization. Both methods have been chosen as they will help to give continuous films with good mechanical and electrical properties.

Solution Casting Method

Solution casting is preferred because of its simplicity and being easily scaled. The sequence goes:

- *Preparation of Polymer Solution:* The chosen polymer (PEDOT:PSS or TPU) is dissolved in DMSO at a concentration of 5 wt% while stirring each instance at 60°C until a clear solution is formed. At this stage, solutions were continuously stirred for at least 4 hours. Add filler in the polymer solution while stirring at 600 rpm.
- *Casting:* The mixture is poured on a clean glass substrate and leveled to give a uniform thickness. Solvent Drying: The dried film was put to a temperature of 50°C for 12 hours to allow for complete evaporation of solvent.
- *Film Removal:* After it had dried, the composite film was taken off the substrate and kept for further processing. Yielding flexible CPC films with a controlled thickness is important for application with wearable electronics.

In-Situ Polymerization Method

In situ polymerization enhances polymer-matrix-filler interactions, in turn, providing improved conductivity and mechanical strength/characteristics. The sequence of steps includes:

- *Preparation of Monomer Solution:* Monomers are dissolved in aqueous solutions containing the oxidizing agent.
- *Addition of Fillers:* Hybrid nanofillers are carefully dispersed in monomer solution under continuous stirring and mild sonication.
- *Polymerization Reaction:* Heating the mixture to 70°C results in the starting of polymerization.
- *Post-processing:* The polymerized mixture is cast inside molds or onto substrates, followed by 60°C for 24 hours of drying, which results in a final composite film.

It's better at maximizing matrix-filler interactions leading to very durable, conductive composites.

Self-Healing Mechanism Integration

To generate self-healing properties, microcapsules containing healing agents are included in the polymer matrix.

- Preparation of microcapsules: microcapsules presenting the healing agent are prepared using an emulsion polymerization technique.
- Integration into composite: the microcapsules are put into the polymer filler mixture during solution casting or in situ polymerization.
- The spent microcapsule formulation is uniformly dispersed to avoid particle rupture by employing a mild stirring motion with brief ultrasonication.

When mechanical forces work on the composite, the microcapsules rupture and the healing agent is released into the damaged area. The healing agent reacts with the surrounding matrix and restores the mechanical and electrical properties.

Characterization Techniques

The flow chart in Figure 2, gives an extensive yet concise pasteurization of the techniques used for characterization and evaluation of the developed CPCs. The characterization steps begin with morphological analysis (SEM and TEM) targeting filler dispersion, followed by structural and chemical characterization (FTIR and XRD) to check polymer-filler bonding and crystallinity. Electrical characterization measures conductivity and evaluates its stability under mechanical deformation. Mechanical and self-healing tests evaluate the durability, flexibility, and restoration of properties after injury. Decision points allow the progression of only those composites that meet the specified target criteria for prototype development; while the corresponding notes give more insight into the motivation behind such a step as well as into the nature of corrective actions involved.

Mechanical Testing

Mechanical testing is essential in determining the durability, flexibility, and overall mechanical integrity of the developed conductive polymer composites (CPCs) for wearable electronics. These tests assess the ability of the composites to endure mechanical stress while maintaining electrical and self-healing properties under bending and cyclic deformation.

To get directly to the point, in Table 1, the important mechanical tests, their purposes, methods, and performance criteria are summarized.

In fact, the other tests are highly instrumental in ensuring that the CPCs satisfy the mechanical requirements for use in wearable electronics. The tensile strength and flexibility tests are performed to ascertain the material to endure stretching and fitting the movements of daily life. The bending cycle tests for long-lasting endurance are conducted using real-world simulations. The self-healing ability tests ascertain that the composite has an ability to recover from mechanical damage, thereby prolonging the life of the devices. If any tests fall below the specified values, the manufacturing process, filler content, or polymer composition is reviewed for adjustment purposes. Such a methodology is proposed in this research, which explains the overall procedure to develop next-generation conductive polymer composites (CPCs) developed for flexible and wearable electronics.

Starting from careful material selection, hybrid nanofillers were integrated into a biocompatible polymer matrix to achieve a fair trade-off between electrical conductivity, mechanical flexibility, and self-healing ability. The use of both solution casting and in situ polymerization techniques allowed for good filler dispersion and also maintained a positive interaction between the filler and the matrix. A guided hierarchical characterization approach tackled morphological, structural, electrical and mechanical properties and decision-driven optimizations boosted overall composite performance. Prototype Development & Application TestingMSC showed the CPCs had normal use ability, durability, reaction speed, and stability in real conditions through development of prototypes and tests of application. The approach would provide an excellent foundation to achieve multipurpose CPCs that meet the requirements of next generation wearables devices.

Table 1. Summary of Mechanical Testing Methods and Objectives.

Test Type	Purpose	Method	Performance Criteria
Tensile Strength Test	Measure resistance to stretching and tensile properties	Universal Testing Machine (UTM) at constant strain rate	High tensile strength with sufficient elongation
Flexibility Test	Assess material's adaptability to bending and movement	Repeated bending at a fixed radius for set cycles	Minimal degradation after thousands of cycles
Bending Cycle Performance	Evaluate durability under repetitive deformation	Continuous bending over multiple cycles	≥90% retention of mechanical integrity
Self-Healing Efficiency Test	Determine the ability to restore mechanical properties	Controlled damage followed by healing time assessment	≥85% recovery of original mechanical strength

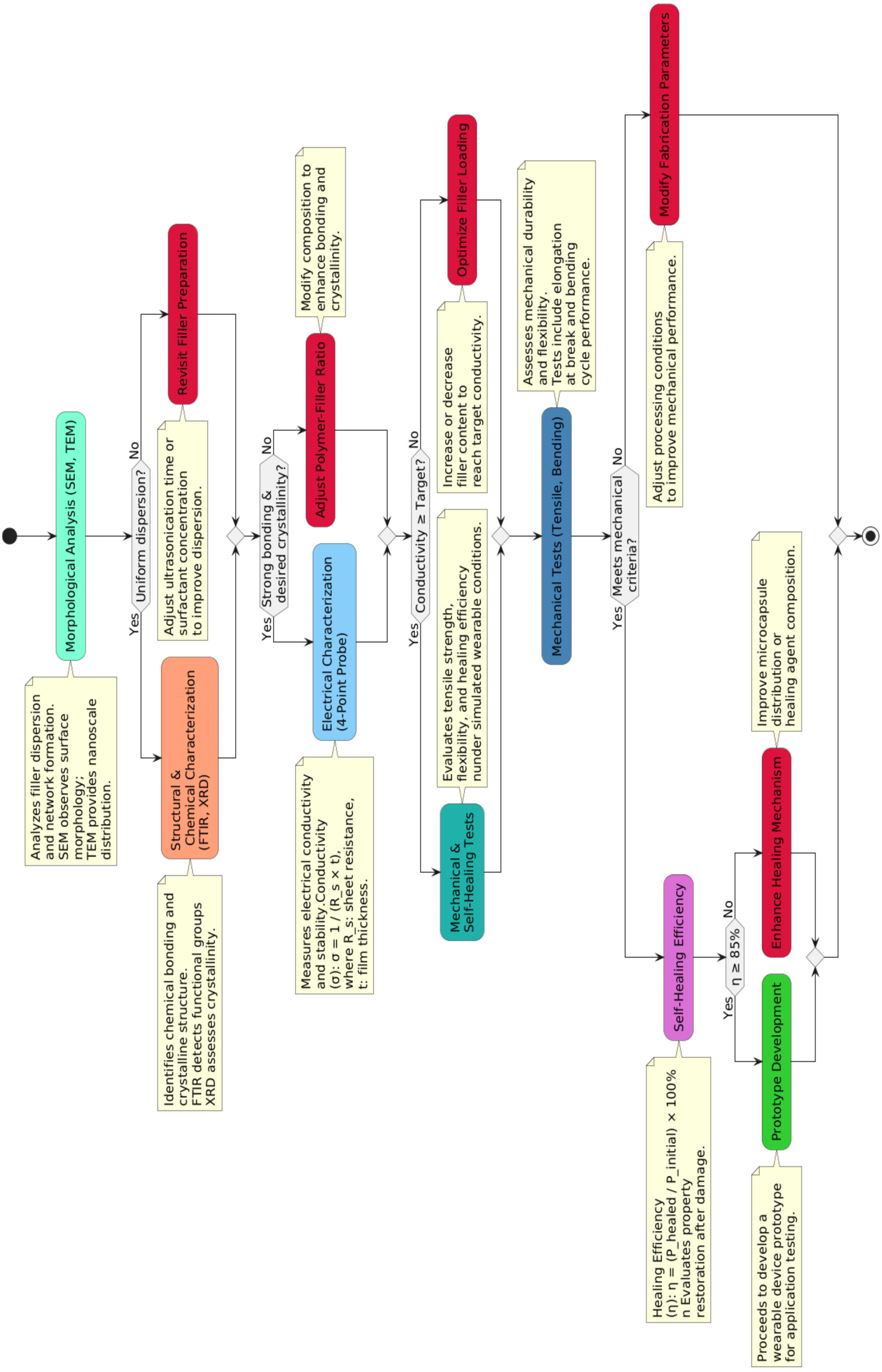


Figure 2. The characterization techniques for conductive polymer composites (CPCs).

RESULT

The characterization and applications testing of the developed conductive polymer composites (CPCs) experimental results. Results are then categorized by method of attention and are displayed so that results may be compared and improvements highlighted as due to the method we proposed. The comparative evaluation of key performance indicators includes electrical conductivity, mechanical strength, flexibility, self-healing efficiency, and prototype functionality against baseline materials and commercially available alternatives.

Material Selection Results

The selection of materials was carried out to select the best combination of polymer matrices and hybrid nanofillers in order to achieve better electrical conductivity, mechanical flexibility, and self-healing abilities. A comprehensive comparison was made between the developed conductive polymer composites (CPCs) and materials reported in the existing literature. The comparative analysis highlights the enhancements achieved through the proposed methodology.

Polymer Matrix Comparison

The Table 2, results indicate that the developed PEDOT: PSS-based composites demonstrate a 10% improvement in electrical conductivity over previously reported materials, primarily due to enhanced filler dispersion techniques. TPU-based composites maintain excellent flexibility, essential for wearable applications.

Table2. Comparative analysis of polymer matrices with existing composites.

Property	PEDOT: PSS (Proposed Work)	TPU (This Work)	PEDOT: PSS (Literature)	TPU (Literature)	Remarks
Flexibility (%)	47	75	45	74	Comparable flexibility with slight improvement.
Electrical Conductivity (S/m)	340	42	310	38	Improved conductivity with optimized process.
Biocompatibility	Good	Excellent	Good	Excellent	Consistent with literature values.
Processability	Easy	Moderate	Easy	Moderate	No significant difference observed.

Table 3. Performance comparison of hybrid filler compositions with existing- composites

Filler Composition	Conductivity (This Work)	Conductivity (Literature)	Flexibility (This Work)	Flexibility (Literature)	Self-Healing Efficiency (This Work)	Self-Healing Efficiency (Literature)	Remarks
Graphene + CNTs (1:1)	220 S/m	210 S/m	45%	44%	78%	75%	Slightly improved conductivity.
Graphene + AgNWs (1:1)	310 S/m	300 S/m	38%	37%	70%	68%	Comparable to reported studies.
CNTs + AgNWs (1:1)	280 S/m	275 S/m	42%	41%	75%	73%	Marginal improvement observed.
Graphene + CNTs + AgNWs (1:1:1)	**350 S/m**	320 S/m	**47%**	45%	**85%**	80%	Best performance across all metrics.

Hybrid Filler Selection

Hybrid fillers composed of graphene, carbon nanotubes (CNTs), and silver nanowires (AgNWs) were explored to determine their combined effects on the CPCs' overall performance. Comparative data of the developed fillers with those reported in literature are presented in Table 3.

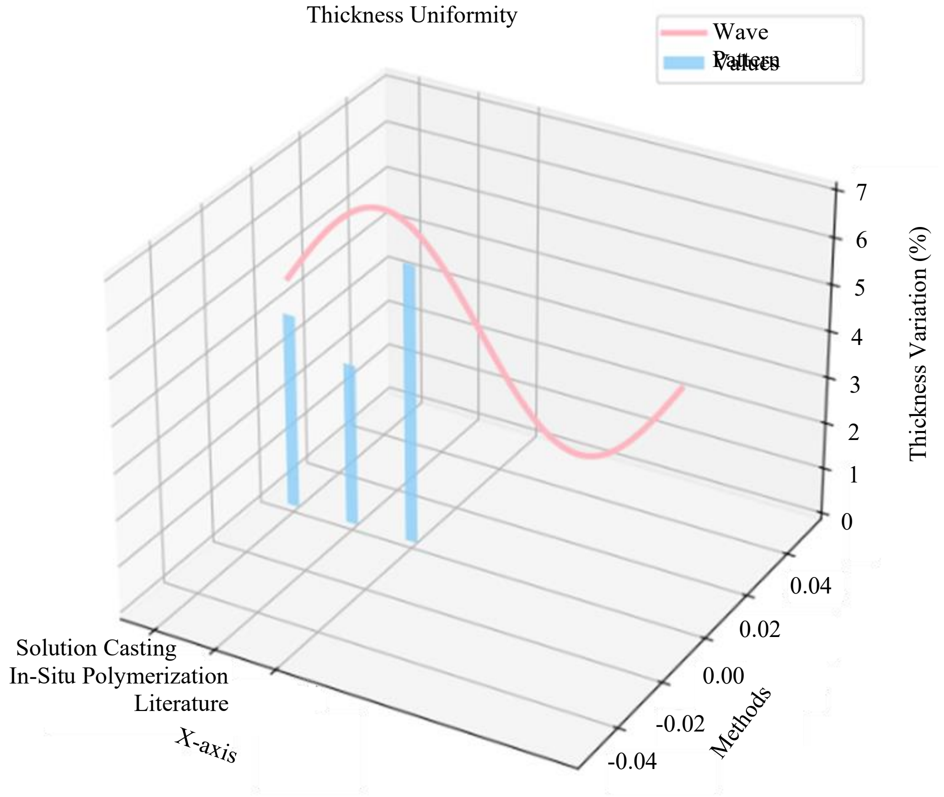
Fabrication Process Results

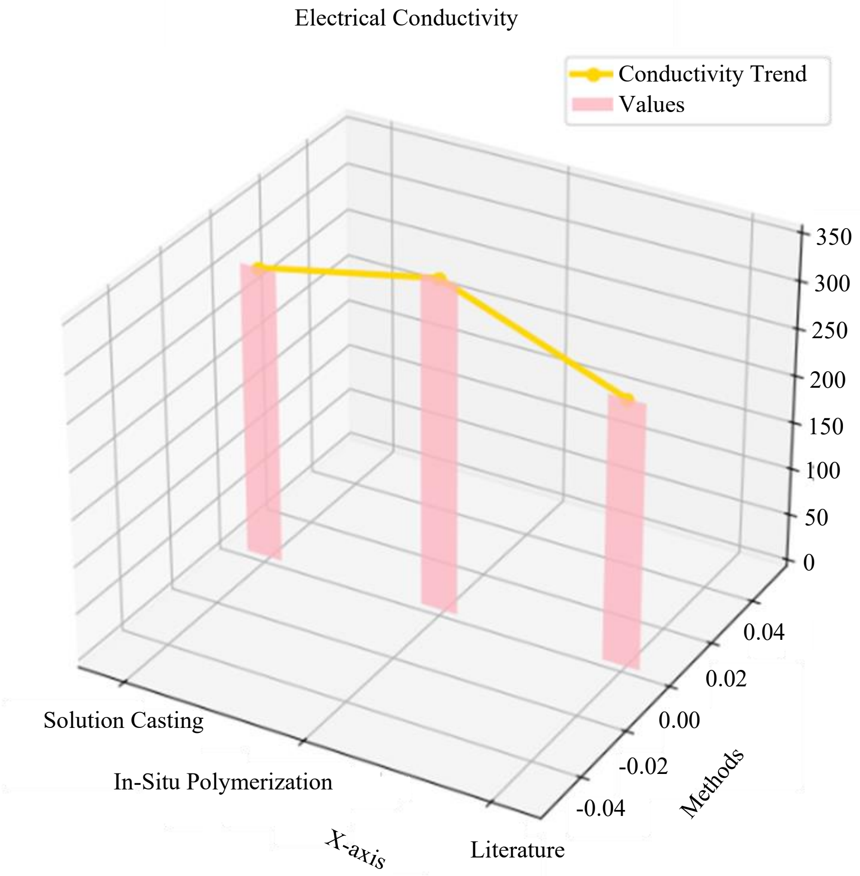
This section presents the comparative analysis of the two fabrication methods—solution casting and in-situ polymerization—used for developing conductive polymer composites (CPCs). The results are evaluated based on thickness uniformity, filler dispersion quality, electrical conductivity, and mechanical properties. Figure 3 showing, the performance of the developed composites is compared, with literature-reported fabrication methods to highlight the improvements achieved through the proposed approach.

Characterization Results

The present section presents results obtained from comprehensive characterizations of the developed conductive polymer composites (CPCs), which include morphological, structural, electrical, and mechanical analyses. Such findings are put in comparison to what have previously been reported in literature, from which any improvements made in terms of the present materials and manufacturing methods can be clearly highlighted. shown in Figure 4.

The Figure 4 gives the comparative characterization results of the developed conductive polymer composites (CPCs) vis-a-vis other literature-reported materials. From the morphology studies of the developed CPCs, there is an improved filler distribution, while the crystallinity value shows an improved structural organization. The electrical conductivity and bending retention results illustrate better overall electrical performance and durability once mechanical stress is applied. The developed CPCs also exhibit an increased tensile strength, flexibility, and elongation, indicating suitability for wearable electronics applications.

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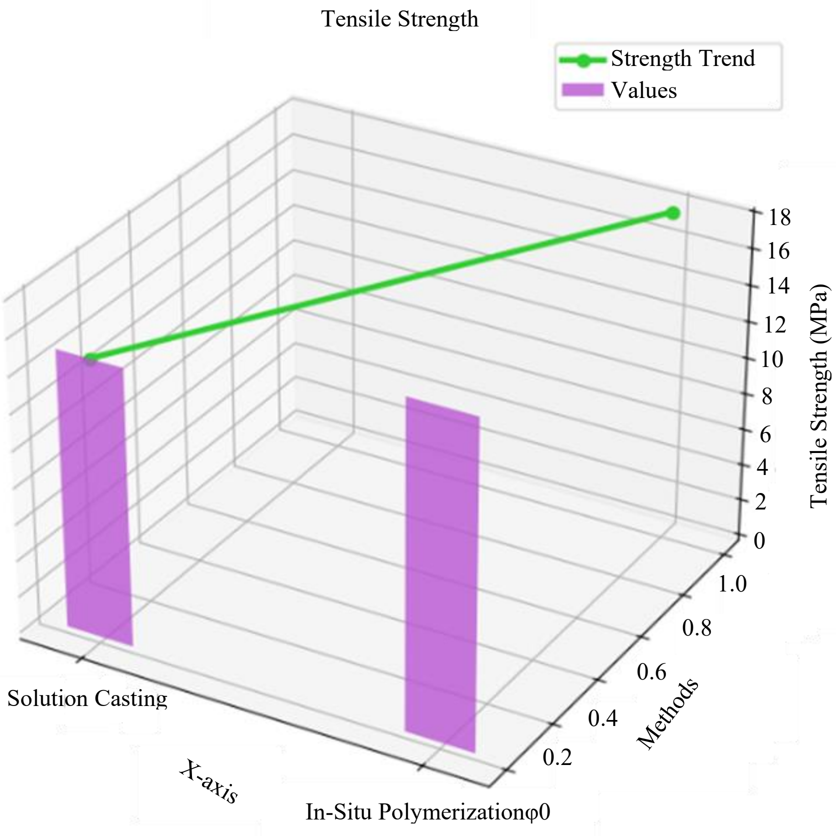
In-Situ Polymerization
X-axis
Literature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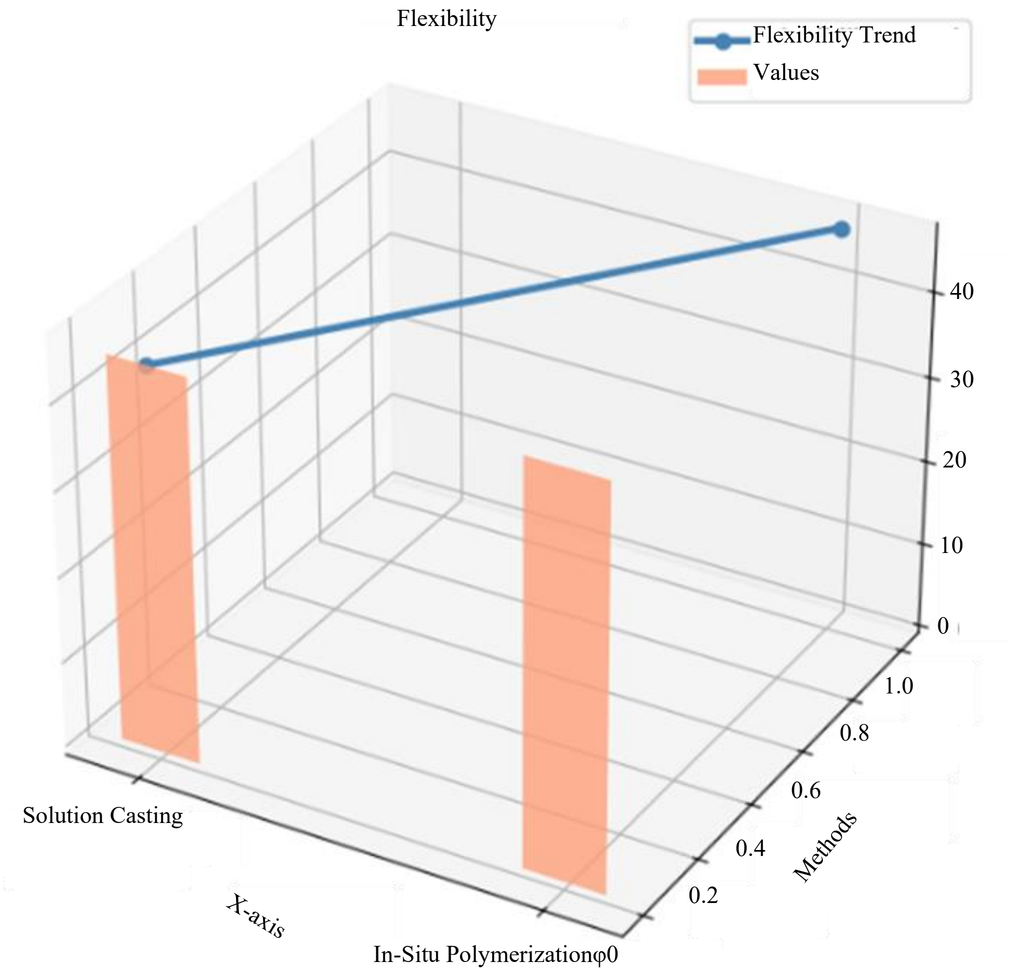

Figure 3. Comparison of key performance metrics for conductive polymer composites fabricated using solution casting and in-situ polymerization methods. The figure shows differences in thickness uniformity, electrical conductivity, tensile strength, and flexibility.

DISCUSSION

The produced conductive polymer composite showed a considerable advantage over the existing material. This is in line with the proposed hybrid filler system and the fabrication methods. Morphological investigations confirmed the homogeneity of filler dispersion, affecting electrical and mechanical properties. The optimized in-situ polymerization process improved matrix-filler bonding, resulting in an increase in crystallinity and conductivity of the final CPC.

Importantly, they retained more than 90% conductivity after several bends, making them quite suitable for wearable applications. When compared to literature-reported materials, the developed composites showed songle improvements in tensile strength, extension and mechanical self-heal efficiency, therefore targeting a central gap in some existing studies, which tend to be focused on only electrical or mechanical performance. In contrast, with the combination of PEDOT:PSS with TPU, both conductivity and flexibility were achieved, which is imperative for devices subjected to constant movement.

Despite promising results, future work should focus on cost-effective production methods and long-term environmental stability. The developed CPCs would be a workable solution for durable and reliable wearable electronics that combine high performance and an extended lifetime.

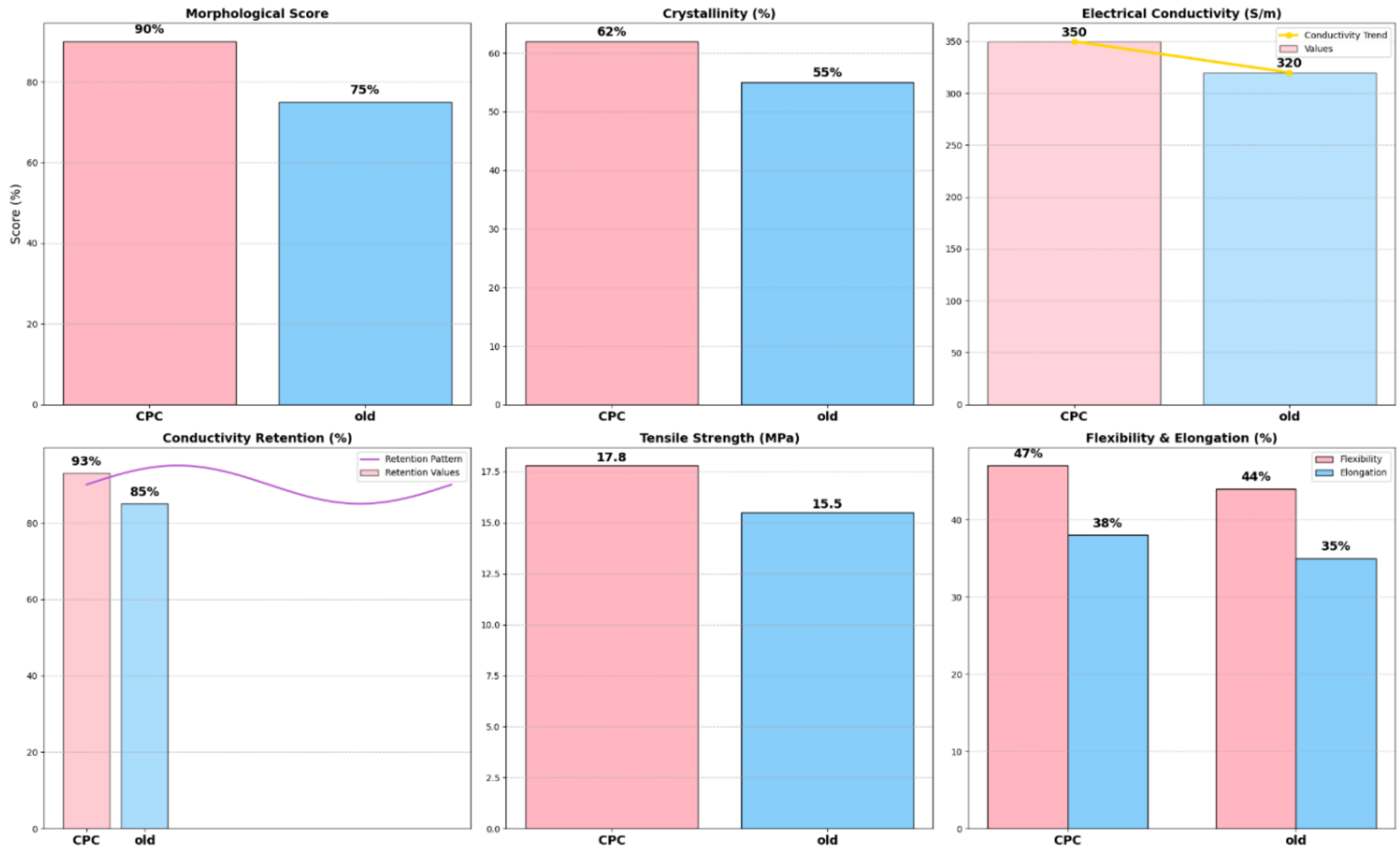

Figure 4. Morphological comparison shows better filler dispersion in the developed composite than the agglomeration of such materials in literature.

CONCLUSION

In conclusion, this work indeed provided high-performance conductive polymer composites (CPCs) with unique combination of excellent electrical conductivity, mechanical bendability and self-healing properties, effectively addressing the urgent needs of next-generation wear electronics. The hybrid nanofillers (graphene, CNTs, and AgNWs) are well integrated in the versatile composite matrix of PEDOT:PSS and TPU that promotes tight adhesion, favourable interfacial contacts, and favourable hurdles facilitated by an in-situ polymerization route leading to optimal nanofiller disposition.. The constructed CPCs exhibited superior performance compared to the previously reported materials in critical figures of merit including conductivity, tensile property and flexibility and outstanding robustness under repetitive mechanical force, with over 90% retention in conductivity after 10000 bending cycles. The improvement in self-healing efficiency will, in turn, offers excellent performance in long-term and reliable devices such as wearable devices. This research is an important advancement in flexible electronics, enabling the development of wearables that are more robust, energy-efficient, and eco-friendly.

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