



Review

Environmentally Friendly PLA-Based Conductive Composites: Electrical and Mechanical Performance

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Abstract

This review investigates recent progress in the field of PLA-based conductive composites for 3D printing. First, it introduces PLA as a biodegradable thermoplastic polymer, describing its processing and recycling methods and highlighting its environmental advantages over conventional polymers. In order to evaluate its printability, PLA is briefly compared to other commonly used thermoplastics in additive manufacturing. The review then examines the incorporation of conductive fillers such as carbon black, carbon nanotubes, graphene, and metal particles into the PLA matrix, with a particular focus on the percolation threshold and its effect on conductivity. Critical challenges such as filler dispersion, agglomeration, and conductivity anisotropy are also highlighted. Recent results are summarized to identify promising formulations that combine improved electrical performance with acceptable mechanical integrity, while also emphasizing the structural and morphological characteristics that govern these properties. Finally, potential applications in the fields of electronics, biomedicine, energy, and electromagnetic shielding are discussed. From an overall perspective, the review highlights that while PLA-based conductive composites show great potential for sustainable functional materials, further progress is needed to improve reproducibility, optimize processing parameters, and ensure reliable large-scale applications.

Keywords: PLA-based conductive composites; 3D printing; polymer composite; mechanical properties; percolation threshold; electrical conductivity

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1. Introduction

The growing demand for environmentally friendly materials has helped maintain scientific interest in biodegradable polymers, particularly polylactic acid (PLA) [1]. PLA is a polymer derived from renewable resources such as potato, sugar and starch, and it is widely recognized for its strong mechanical properties, biodegradability [2,3], and suitability for additive manufacturing. These properties allow PLA to be used in different fields, including packaging, 3D printing, and biomedical applications [4–7].

Despite its many advantages, PLA's inherently insulating nature significantly limits its potential for applications that require electrical conductivity. To overcome this limitation, research has focused on developing conductive PLA-based composites by incorporating conductive fillers [8–10]. These advancements expand the use of PLA to more

advanced technical fields, including smart sensors, printed circuits, and flexible electro-magnetic devices [11].

In this regard, a lot of research has looked into adding conductive fillers to the PLA matrix to create multipurpose composites that combine electrical conductivity and mechanical performance [12–15]. The most frequently researched fillers include metallic particles [16], graphene in different forms [17], carbon black (CB) [13,18], carbon nanotubes (CNT) [19], and hybrid fillers [20]. These reinforcements significantly influence the final properties of the material due to their structure and their ability to form conductive networks [19,21].

In this context, the present article offers a comparative analysis of published research on PLA-based conductive composites, with a focus on the relationship between the type of conductive filler and the resulting mechanical and electrical performance. The aim is to highlight the most promising formulations and identify current trends in the field.

In order to select the most relevant works, a bibliographic search was carried out in the Scopus, Springer, and Wiley databases covering the period from 2014 to September 2025, from which we retained only peer-reviewed, published articles dealing specifically with PLA composites incorporating conductive fillers and analyzing both mechanical (modulus of elasticity, tensile strength, elongation, etc.) and electrical (conductivity, resistivity, etc.) properties.

A bibliometric analysis is presented in Figure 1, which highlights a continuous and marked growth in the number of scientific publications on conductive composites-based PLA. A significant increase can be observed from 2014 onwards, reflecting the scientific community's growing interest in this multidisciplinary field. Scopus shows the most pronounced increase, particularly from 2017 onwards, with a peak in 2024 of 50 publications. Springer and Wiley show more limited but steady upward trends, particularly after 2020. The decrease in the number of articles published in 2025 is explained by the fact that articles were counted up to September at the time of writing.

The number of publications is doubling almost every two years. This trend reflects the growing importance of flexible electronics, multifunctional materials and advanced polymers, and in particular polymers with electrical properties. The convergence of 3D printing, conductive nanomaterials and biodegradable polymers such as PLA has opened up new research prospects.

This bibliometric trend reflects the growing importance of flexible electronics, multifunctional materials, and advanced polymers, particularly polymers with electrical properties. The convergence of 3D printing towards conductive nanomaterials (graphene, CNT and CB) and biodegradable polymers such as PLA has opened up new research prospects in printable and biodegradable electronics. The bar chart in Figure 2 shows the disciplinary distribution of the publications reviewed. The majority of publications are in materials science (with 76.5% in Scopus, 30.55% in Springer, and 63.82% in Wiley databases), engineering (with 39.047% in Scopus, 38.88% in Springer, and 25.53% in Wiley databases), and chemistry (with 45.714% in Scopus, 18.055% in Springer, and 31.91% in Wiley databases), followed by physics, chemical engineering, biomedical engineering and other disciplines.

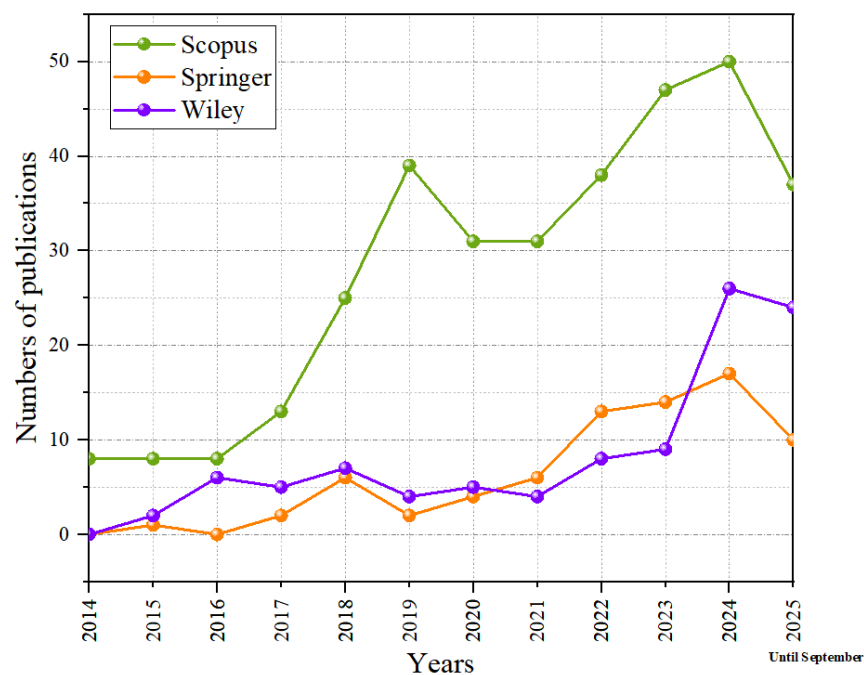


Figure 1. Number of publications on PLA-based conductive composites indexed in Scopus, Springer, and Wiley databases from 2014 to September 2025.

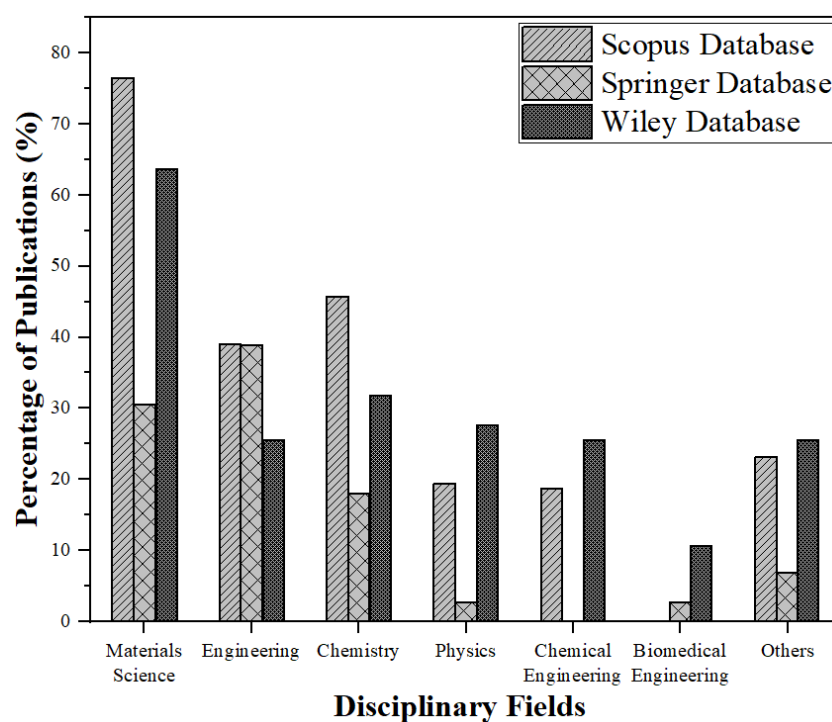


Figure 2. Disciplinary distribution of Conductive PLA composites publications under: Scopus database, Springer database, and Wiley database.

2. Polymer Matrix PLA

2.1. Process of PLA Fabrication

The Fused Deposition Modeling (FDM) techniques of pure PLA polymer filaments have emerged as the primary source of thermoplastics in the three-dimensional (3D) printing industry throughout the last 20 years. The production of PLA is considered to be more environmentally friendly, as it is based on a multi-stage process, starting with renewable

agricultural resources such as corn, sugarcane, or manioc. These crops are transformed into starch by fermentation and extraction, then undergo enzymatic hydrolysis, which breaks down the complex carbs into glucose molecules [22].

The resulting glucose is then converted into lactic acid through microbial fermentation, typically using specific *Lactobacillus* strains [23]. To synthesize PLA, lactic acid is either polymerized directly or transformed into a cyclic dimer called lactide, which then undergoes a cycle-opening polymerization to obtain a high-molecular-weight PLA. This polymer is then granulated and transformed into filaments using techniques such as extrusion or fused filament fabrication (FFF) for 3D printing [24,25]. The final step is the additive manufacture of components or functional objects using PLA filament as a raw material [26].

Printed PLA can be recycled mechanically using a shredder or grinder or chemically by industrial composting. The compost process requires controlled conditions, including high temperature (often over 58 °C), high humidity, and intense microbial activity. During biodegradation, PLA breaks down into carbon dioxide, water, and organic matter. The carbon dioxide released is then captured by plants via photosynthesis, thanks to solar energy, contributing to the growth of new crops used as raw material to produce PLA again, looping a sustainable production cycle. This composting process represents an ecological end-of-life solution, enabling the material to be reintegrated into the environment without leaving behind persistent plastic waste [27].

This entire production chain illustrates PLA's status as a bio-sourced and potentially biodegradable material, as shown schematically in Figure 3.

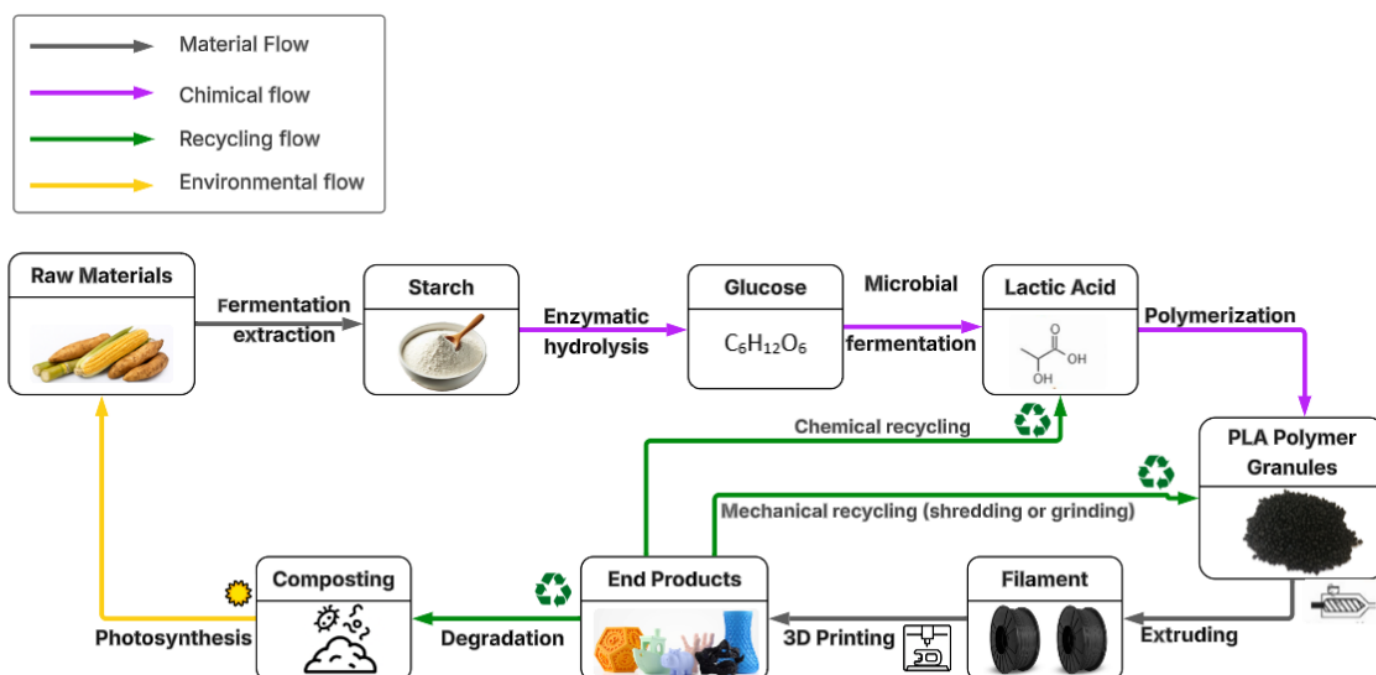


Figure 3. Overview of the global production flow of PLA.

2.2. Mechanical Comparison of PLA with Common Basics Thermoplastics

Recently, the growing use of polymers has become essential in various sectors such as the packaging, injection molding, blow molding, thermoforming, film forming, and biomedical industries [28,29]. Common polymers such as PLA, ABS, PP, PVC, PE, and PET offer a wide range of mechanical properties [30]. The PLA is characterized by its high Young's modulus from ~3.5 to 3.7 GPa and high tensile strength around ~49–59 MPa, reflecting good rigidity but low ductility, with limited elongation at break from ~4 to 7%. In

contrast, PE has very low stiffness around ~0.21 GPa and limited mechanical strength of ~11.7 MPa, but this is compensated by a higher deformation capacity of ~15.4%, making it suitable for flexible applications. In addition, with its moderate modulus around ~1.97 GPa and exceptional elongation of ~167%, soft PVC shows highly ductile behavior, despite its relatively modest tensile strength around ~26.6 MPa. In the case of PP, which has a moderate stiffness of ~1.3 GPa, a yield strength of ~32 MPa, and an elongation of ~70%, it combines flexibility with good mechanical strength. PET, on the other hand, has a high tensile strength of ~60 MPa but moderate ductility around ~8%, while ABS represents a good compromise with intermediate stiffness (~2–3 GPa), tensile strength of around 36–40 MPa, and appreciable ductility between ~21% and 50%. Accordingly, each polymer possesses a distinct balance between stiffness, strength and deformability, which orients their choice according to the specific mechanical requirements of the desired applications.

Compared to other typical polymers, PLA combines strong mechanical performance, high rigidity, ease of 3D printing, and biodegradability, making it an ideal matrix for the development of conductive composites through the incorporation of fillers such as carbon black, graphene, or carbon nanotubes. Furthermore, PLA is a low-cost and widely available polymer, which increases its appeal across various engineering fields.

Table 1 illustrates a comparative summary to benchmark PLA against common thermoplastics frequently used in additive manufacturing; the mechanical values in the table do not remain constant and may vary depending on several factors, such as manufacturing process, processing conditions, using some additives, operating temperature, and molecular weight changes that could affect material crystallinity.

Table 1. Comparative mechanical properties of PLA and other conventional polymers.

Polymers	Young Modulus (GPa)	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation at Break (%)	Refs
PLA (Polylactic Acid)	~3.6	-	~60	~6	[31]
	~3.734	~49.58	-	~4.68	[32]
	~3.5	~59	~70	7	[4,33]
ABS (Acrylonitrile Butadiene Styrene)	~2.1555	~36.10	~26.73	~30 Ductility: ~21.34	[34,35]
	From ~2.6 to ~3	~40	-	~50	[33]
PP (Polypropylene)	~1.3	-	~32	70	[36]
Soft PVC (Polyvinyl Chloride)	~1.971	~26.6	-	~167.2	[37]
PE (Polyethylene)	~0.21	~11.7		~15.43	[38]
PET (Polyethylene Terephthalate)	~1.094	~60.6	-	~8.1	[39]

2.3. Comparing 3D Printing Parameters of Common Thermoplastic Polymers

The performance of printed FDM 3D parts is directly impacted by a number of critical parameters, including extrusion temperature, bed temperature, print speed, layer orientation, fill density, and layer thickness. These parameters significantly change the viscosity of the molten polymer, which in turn influences the mechanical properties of the final part [40,41]. They also have a significant impact on internal stress generation and interlayer adhesion, with various consequences according on the material. Furthermore, the quality and reproducibility of printed parts are significantly impacted by printability difficulties

including warping, layer delamination, and moisture sensitivity, especially when it involves hygroscopic polymers such as nylon.

Previous earlier research has looked at how these characteristics affect thermoplastic polymers in an attempt to maximize their mechanical performance. Two of these research projects concentrated on PLA and ABS materials. According to Syaefudin et al. [42], tensile strength is significantly impacted by printing direction, with 0° orientation providing the greatest results. Strength decreases by 52.8% for PLA and 44.3% for ABS when moving from 0° to 90°. Meanwhile, Shergill et al. [43] showed that both polymers' mechanical characteristics (tensile strength and strain at break) are negatively impacted by increasing layer thickness, with PLA being more significantly affected.

In addition, Kartal and Kaptan's study [44] investigated how printing speed affected the mechanical characteristics and manufacturing quality of PLA parts made using FDM. According to the findings, increasing speed significantly cuts down on production time, but it also has a number of limitations, including a decrease in sample mass (about 12%), a drop in Shore D hardness, a notable drop in tensile strength (−27%), and an increase in surface roughness and part porosity.

In the same perspective, Adarsh and Nagamadhu's study [45] concentrated on optimizing printing parameters (layer thickness, fill ratio, and nozzle and bed temperature) in order to enhance mechanical performance and reduce warpage of printed PEEK parts. The authors demonstrated that increasing fill, nozzle and bed temperatures greatly enhanced PEEK's tensile and compressive strengths, which reached 71.4 MPa and 167 MPa, respectively. A fill ratio of 60%, a bed temperature of 130 °C, a nozzle temperature of 400 °C, and a layer thickness of 0.16 mm all minimized warpage.

These bibliographic findings highlight how printing factors have a significant impact on the mechanical characteristics of 3D-printed thermoplastic polymers. However, it is also critical to keep in mind that every polymer type has unique printing and performance limitations, which have a direct impact on the produced components quality.

In this context, Table 2 presents a comparative overview of the primary 3D printing parameters (by FDM) for the thermoplastic polymers that are frequently used: PLA, ABS, PP, PVC, HDPE, PETG, PEEK and Nylon. It shows not only the ideal ranges for extrusion temperature, bed temperature, and print speed, but also useful factors like adhesion to the print bed, each material's unique limitations, and practical advantages [46].

PLA, for example, is widely recognized for its high stiffness, excellent bed adhesion, and ease of printing. It is compatible with most consumer FDM printers thanks to its relatively low extrusion temperature around ~190 to 210 °C and stability over a wide range of printing speeds from ~40 to 80 mm/s. However, its application in challenging mechanical environments is limited due to its fragility and low heat resistance. In contrast, ABS requires stricter printing conditions, including a heated bed around ~90 to 110 °C with a higher extrusion temperature about 220 to 260 °C and the use of a closed chamber to minimize warping. Although ABS offers greater strength and is easier to process after printing than PLA, it remains difficult to print due to its significant thermal shrinkage, risk of delamination, and strong odor emission during extrusion. PP (polypropylene) and HDPE (high-density polyethylene) are appreciated for their flexibility, low density, and excellent chemical resistance, but printing them is particularly difficult due to their very poor adhesion to the platen and high thermal contraction. They require specific adhesion surfaces, such as PP ribbons, as well as very precise temperature and print speed settings. HDPE also requires a high bed temperature around 130 °C and remains difficult to dimensionally stabilize. PVC, on the other hand, has good mechanical strength and is fireproof, which accounts for its extensive use in HTA electrical cables [47]. However, because of its processing limitations and the production of harmful gasses (HCl) at high temperatures, PVC is not widely used in 3D printing. It requires relatively low extrusion temperatures (~180–

200 °C) and slow printing speeds (~10–30 mm/s). PETG, by contrast, is an interesting compromise between PLA and ABS; it offers improved moisture resistance, strong mechanical strength, and ease of printing. However, it is still susceptible to stringing and may need an adhesive to ensure proper bed adherence. Furthermore, anisotropy is still a major problem in FDM since the printing direction and layer orientation can have a substantial impact on the mechanical and electrical properties, which frequently results in lower conductivity between layers compared conventional ways.

Beyond these conventional polymers, engineering-grade materials such as PEEK and polyamides (PA6 and PA12) provide valuable benchmarks for high-performance applications. PEEK, in particular, offers exceptional thermal, mechanical, and chemical resistance, making it highly interesting for industrial applications, even with its extremely high extrusion around 350 to 420 °C and bed around 120 to 130 °C temperatures and need of a closed chamber. PA6, processed at 230 to 260 °C with a bed around 80 to 90 °C, exhibits high strength and durability but suffers from warping and high moisture absorption, requiring careful drying and controlled printing conditions. PA12, extruded at about 270 °C with a bed near 90 °C, provides better adhesion and less warping than PA6, with good dimensional stability and chemical resistance. When conductive fillers are incorporated into these engineering polymers, further challenges arise. High filler loadings increase melt viscosity and can cause nozzle clogging, while poor dispersion leads to agglomeration and reduced print resolution. On the other hand, well-dispersed fillers not only enhance conductivity but also improve interlayer bonding, thereby mitigating anisotropy.

These analyses show that the choice of polymers and the precise adjustment of printing parameters are closely linked to ensure not only the desired mechanical properties, but also dimensional stability, strong adhesion between layers, and superior overall print quality.

Table 2. Additive manufacturing of common polymers matrix by FFF.

Polymers	Extrusion Temperature (°C)	Bed Temperature (°C)	Print Speed Recommended (mm/s)	Printability & Bed Adhesion	Advantages	Limitations	Refs
PLA (Polylactic Acid)	~190–210	~25–80	~40–80	Easy to print	Ecological, rigid, printable at low T°.	Brittle, poor thermal resistance	[35,48,49]
ABS (Acrylonitrile Butadiene Styrene)	~220–260	~90–110	~40–60	Medium to difficult: Requires a heated bed, adhesive (e.g., glue stick), and a skirt	Resistant, Post-processable	Strong odor, prone to warping, requires enclosed chamber	[35,48,49]
PP (Polypropylene)	~200–230	~90–110	~35–70	Difficult to print: PP-specific tape recommended/poor bed adhesion,	Flexible and chemically resistant.	Difficult to print due to high shrinkage (warping risk)	[50]
PVC (Polyvinyl Chloride)	~180–200	~50–60	~10–30	Difficult to print/Poor natural adhesion (Glue or special adhesives are recommended)	Flame-retardant and mechanically strong	Toxic fumes HCl and degradation risk at elevated temperatures	[51,52]

HDPE (High-Density Polyethylene)	~200–260	~60–130	~25–150	Difficult to print: Significant shrinkage and warping/Poor bed adhesion	Flexible, chemically resistant, hydrophobic, lightweight:	Difficult to print due to high warping risk, needs a high bed temperature	[53,54]
PETG (Polyethylene Terephthalate Glycol)	~220–250	~70–90	~40–60	Easy to print with good inter-layer adhesion/Bed adhesion may require a glue stick or adhesive	Good balance between rigidity and flexibility	Prone to stringing and sensitive to moisture.	[35,48,49]
PEEK (Polyether Ether Ketone)	~350–420	~120–130 °C	~20–60	Difficult to print, requires a hot bed/closed chamber/good property if printed correctly	High thermal, mechanical, and chemical resistance	High cost, warping, thermal convection, difficult crystallization control, sometimes weak adhesion interface	[55–57]
Nylon (PA6: Polyamide 6)	~230–260	~80–90	~40–60	Needs high-temp bed, dries before print	Strong, durable, high mechanical resistance.	Warping, absorbs moisture, requires closed chamber	[58,59]
Nylon (PA12: Polyamide 12)	~270	~90	~40–60	Better adhesion than PA6, less warping	Chemically resistant, dimensionally stable	Still hygroscopic, requires dry storage & hotend > 250 °C	[60]

3. PLA-Based Conductive Composites

3.1. Percolation Threshold of Conductive Fillers in PLA Matrix

In the field of polymer composites, the incorporation of conductive fillers represents an ideal technique for increasing the electrical conductivity of insulating polymer materials such as PLA [29]. These additives promote the creation of conductive networks in the polymer matrix when their concentration exceeds a critical value, known as the percolation threshold. This threshold corresponds to the minimum quantity of filler required to guarantee connection between particles and facilitate the electrical current's flow.

Among the various conductive fillers used to improve the electrical performance of PLA-based composites, carbon fillers such as graphene (GNP), carbon black (CB), and carbon nanotubes (CNTs) are the most extensively studied [61,62]. Each type of filler offers specific advantages in terms of electrical conductivity, mechanical reinforcement, and ease of processing. Moreover, metallic particles and emerging two-dimensional materials, such as transition metal carbides and nitrides (MXenes) [63], present promising pathways to further improve the electrical and thermal properties of composites, exhibiting diverse percolation thresholds.

Another innovative solution for providing conductivity is intrinsically conductive polymers, which are able to conduct electricity naturally thanks to their particular chemical structure, such as polyaniline, polypyrrole, and polythiophene.

Figure 4 shows the percolation thresholds of four types of conductive fillers incorporated in pure PLA matrices under direct current (DC) conditions. The fillers considered are CNTs, CB, GNP, and silver nanowires (Ag NWs). CNTs have a low percolation

threshold of 1 wt%, corresponding to 0.71 vol%, reflecting their high efficiency in forming conductive networks at low concentrations thanks to their elongated structure [14,64,65]. In contrast, CB requires a higher concentration to achieve percolation, with a threshold of 8 wt% (5.5 vol%) [66]. This is due to the quasi-spherical shape of the particles and their less developed contact surface compared with carbon nanotubes. Similarly, graphene nanoplatelets (GNPs) show a threshold of around 7 wt% (4.07 vol%), which is still relatively low compared with their lamellar structure and ability to form efficient conductive paths [67]. And finally, Ag NWs, known for their excellent intrinsic conductivity, reach the percolation threshold at a very low concentration of 0.13 wt% (1.08 vol%), making them extremely high-performance fillers for low-load applications [68]. To summarize, AgNW and CNT are the most effective fillers in general due to their high aspect ratio and their excellent conductivity, while CB and GNP require higher fillers but remain recommended for large-scale processing due to their affordability and ease of processing. Based on this comparison, the main factors influencing the percolation threshold in PLA-based composites are filler morphology, aspect ratio, and dispersion quality.

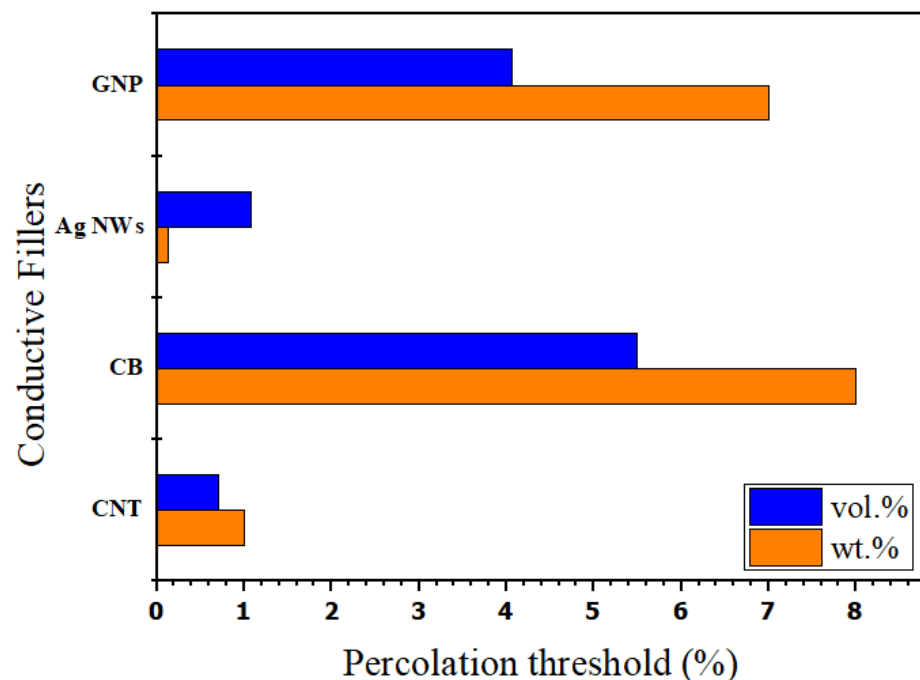


Figure 4. The electrical percolation thresholds of conductive fillers in PLA-based composites (DC regime) [values extracted from Refs. [64–68]].

These results mainly concerned the PLA-only matrix. However, research on dual composites that combine two different kinds of polymers with conductive fillers is also documented in the literature. In this regard, Masarra, N.-A. et al. [69] investigated the impact of polymer processing techniques like compression molding and FFF fused filament deposition manufacturing on the electrical double percolation threshold with graphene nanoplatelets (GNP) using a blend of polylactide (PLA) and polycaprolactone (PCL). The PLA65/PCL35 composition with 10 wt% GNP showed the greatest electrical conductivity performance, exhibiting the double percolation phenomena. In the same context, another study was carried out by Xiang Lu et al. [70] to produce electrically conductive composites based on PLA and recycled HDPE with CB, offering a low electrical percolation threshold and good mechanical properties. The results indicate that the ideal composition is a combination of PLA70/30HDPE/CB composites. Thanks to a co-continuous microstructure and selective distribution of CB in the HDPE phase, this formulation achieved an exceptionally low electrical percolation threshold of approximately 5 wt%.

These composite materials showed remarkable electrical conductivity, reaching up to 15 S/cm with a CB concentration of 15 wt%, while maintaining excellent mechanical properties and enhanced thermal stability.

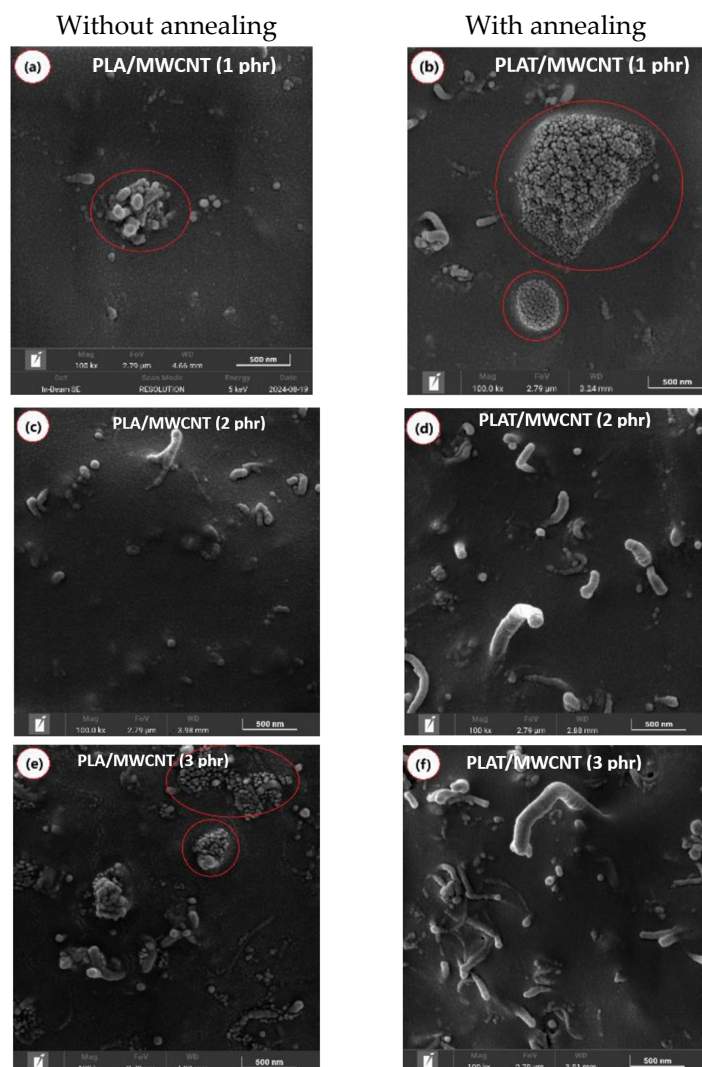
In addition, various research studies have examined the impact of hybrid fillers by combining different types of conductive fillers in a PLA matrix. This could also enhance dispersion, improve mechanical properties and further reduce the percolation threshold thanks to the synergy between fillers. Xuan Zhou et al. [65] carried out a study along these lines to establish the rheological and electrical behavior of composites of PLA/MWCNT-GNP, of PLA/GNP and of PLA/MWCNT for 3D printing applications, their results showing that the aspect ratios of the fillers play a crucial role in determining the overall electrical conductivity of the nanocomposites obtained. The article indicates a relative order of percolation thresholds for binary and ternary composites. It is stated that the percolation threshold of PLA/MWCNT composites is lower than PLA/MWCNT-GNP, which itself lower than PLA/GNP. In a similar perspective, Giner-Grau, S et al. [71] evaluated the impact of nanoadditives consisting of GNPs + CB on the electrical conductivity, mechanical strength and thermal behavior of PLA for 3D printing and injection molding applications. In the same context, Mojtaba Haghgoo et al. [72] have also studied the electrical conductivity and piezoresistivity of hybrid polymer nanocomposites of CNTs and GNPs, developing a conductive network model to examine the influence of tunneling effects and nanofiller subbands under the effect of an electromagnetic field. With a percolation threshold for CNTs set at 0.5 vol%, the model predicted a rapid increase in the electrical conductivity of nanocomposites from 10^{-13} to over 10^{-3} S/m. Smaller GNPs, high intrinsic CNT conductivity, haphazardly oriented CNTs, and the presence of a magnetic field all greatly increase this conductivity. The piezoresistivity of the nanocomposite, which measures the change in resistance in response to deformation, exhibited an increase of 30% at 1.5% deformation and is impacted by the number of subbands and the aspect ratio of the CNTs. Beyond these hybrid fillers, new directions are increasingly looking at innovative production methods. For example, multi-material 3D printing allows PLA-based composites to be incorporated with other functional materials in a single structure, making it easier to create multifunctional devices with customized electrical and mechanical responses. In addition, surface functionalization of fillers is attracting increasing attention, as it can substantially improve dispersion, minimize agglomeration, and optimize adhesion to the PLA matrix, leading to increased electrical conductivity and mechanical performance.

Determining the percolation threshold in PLA-based composites remains difficult despite these advances. The values reported in this context often vary considerably from one study to another, even for equivalent loads, due to differences in dispersion quality, particle morphology, and manufacturing processes. For example, carbon nanotube-based composites sometimes exhibit thresholds below 1 wt%, unlike other studies that report values above 5 wt%. These differences are mainly related to variations in aspect ratio, agglomerations, and the influence of processing techniques used, such as solvent casting or melt spinning. In addition, weak interfacial bonding between fillers and the PLA matrix can limit charge transport and further complicate reproducibility. These limitations underscore the importance of optimizing dispersion methods and carefully comparing studies when interpreting percolation data.

3.2. Structural and Morphological Characterization

Recent studies have clearly demonstrated that the structural and morphological characteristics of PLA-based conductive nanocomposites strongly influence their mechanical and electrical performances [7,73–76]. The goal is to make a three-dimensional (3D) conduction network by adding conductive fillers. Through SEM observations, for example, Urbano da Silva et al. [77] determined that adding 2 to 4 phr of MWCNT to PLA/multi-

walled carbon nanotube (MWCNT) composites enhanced nanotube distribution and decreased interparticle distances. Molecular rearrangements during thermal annealing may have directed CNTs in the direction of PLA's amorphous interspherulitic areas. An interconnected CNT network developed in annealed PLA/MWCNT (4 phr) nanocomposite materials, as shown in Figure 5. Structural and vibrational analyses using X-ray diffraction (XRD) patterns confirmed these observations. The XRD results for unannealed PLA/MWCNT composites displayed an amorphous profile without crystalline peaks. By contrast, annealed PLA/MWCNT samples exhibited well-defined crystalline reflections at $2\theta = 17^\circ$ and $2\theta = 19.4^\circ$, corresponding to the (110)/(200) and (203) planes, as illustrated in Figure 6. In addition, they reported that CNTs act as nucleating agents, improving crystallinity, with a maximum degree reaching 63.7% for PLA/MWCNT composites (2 phr). FTIR analysis also confirmed these findings; the authors discovered that while the addition of MWCNT did not substantially alter PLA's primary absorption bands, annealed PLA/MWCNT composites displayed a new band at about 922 cm^{-1} , suggesting improved crystallinity; see Figure 7.



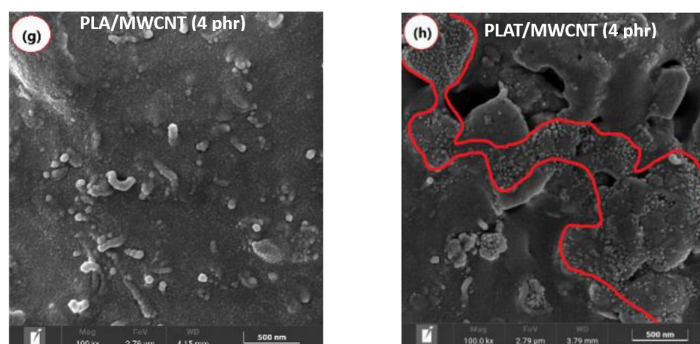


Figure 5. SEM micrographs (100 kx) illustrating the morphological evolution of PLA/MWCNT nanocomposites containing from 1 to 4 phr of MWCNTs, comparing unannealed (a,c,e,g) and annealed (b,d,f,h) samples [Adapted from [77], distributed under the terms and conditions of the CC BY license <https://creativecommons.org/licenses/by/4.0/>].

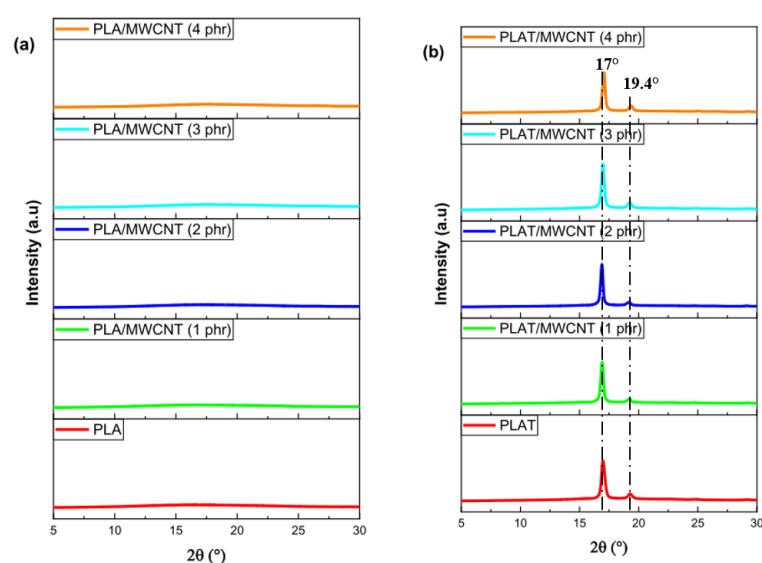


Figure 6. XRD patterns of pure PLA and PLA/MWCNT nanocomposites with varying MWCNT contents from 1 to 4 phr: (a) without annealing; (b) with annealing [Adapted from [77], distributed under the terms and conditions of the CC BY license <https://creativecommons.org/licenses/by/4.0/>].

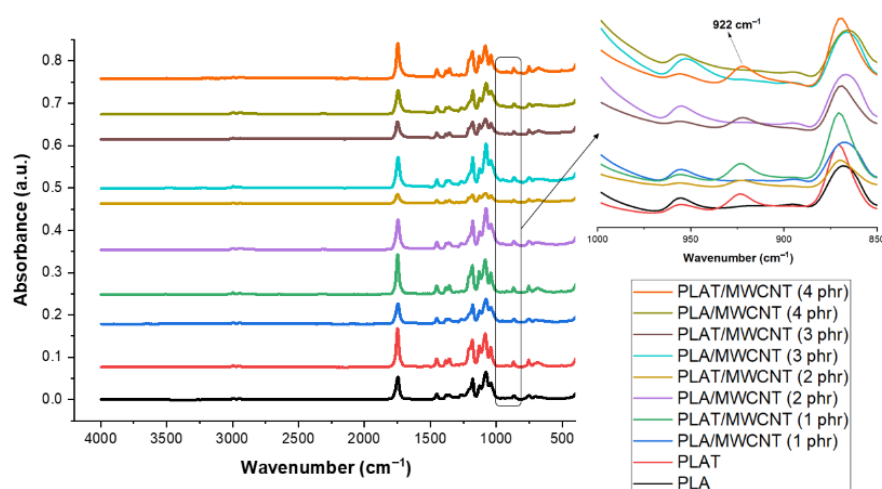


Figure 7. FTIR curves of pure PLA and PLA/MWCNT nanocomposites with varying MWCNT contents from 1 to 4 phr, with and without annealing [Reproduced from [77], distributed under the terms and conditions of the CC BY license <https://creativecommons.org/licenses/by/4.0/>].

Another study, based on SEM micrographs, was conducted by França et al. [78] on PLA composites containing 0.1 and 0.3 wt% graphene, respectively. The observations presented in Figure 8 showed a homogeneous distribution of constituents within the matrix, particularly calcium, aluminum, and carbon, reflecting a high degree of filler-matrix integration. Furthermore, for these PLA/graphene composites, the authors confirmed a predominantly amorphous nature, although a broad peak around $2\theta \approx 20^\circ$ and a shoulder near $2\theta \approx 26^\circ$, observed for both contents, suggest the (002) reflection of graphene, see Figure 9.

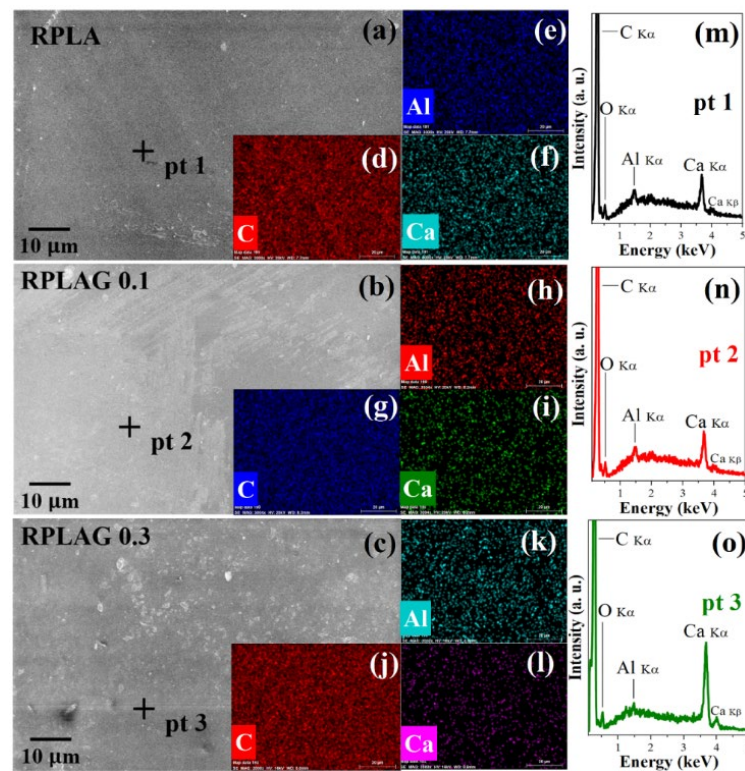


Figure 8. SEM/EDS analysis of RPLA and RPLAG (0.1–0.3 wt%) samples: (a–c) surface micrographs showing EDS measurement points; (d–f) elemental maps of C, Al, and Ca; (m–o) corresponding EDS spectra [Reproduced from [78], distributed under the terms and conditions of the CC BY license <https://creativecommons.org/licenses/by/4.0/>].

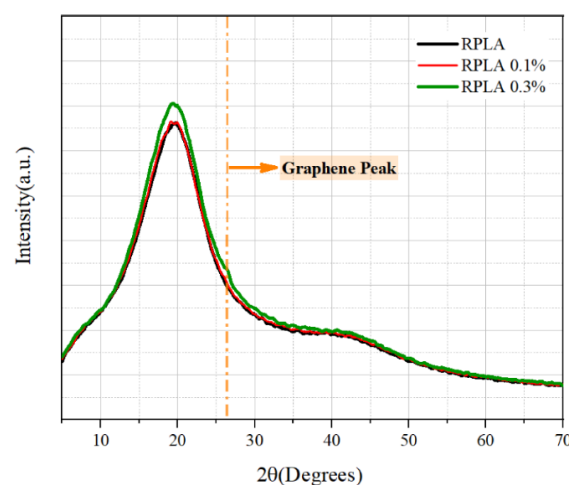


Figure 9. XRD patterns of RPLA and RPLAG (0.1–0.3 wt%) samples, showing an amorphous profile for all compositions [Reproduced from [78], distributed under the terms and conditions of the CC BY license <https://creativecommons.org/licenses/by/4.0/>].

The research by C. Sánchez-Rodríguez et al. [79] corroborated these results with Raman spectroscopy in Figure 10, verifying the effective incorporation of graphene oxide into the PLA matrix at 1585 cm^{-1} observed in the PGO (PLA + graphene oxide GO) and PGL (PLA + GO + ionic liquid [Bmpyr]PF₆) samples and providing additional information on interfacial interactions.

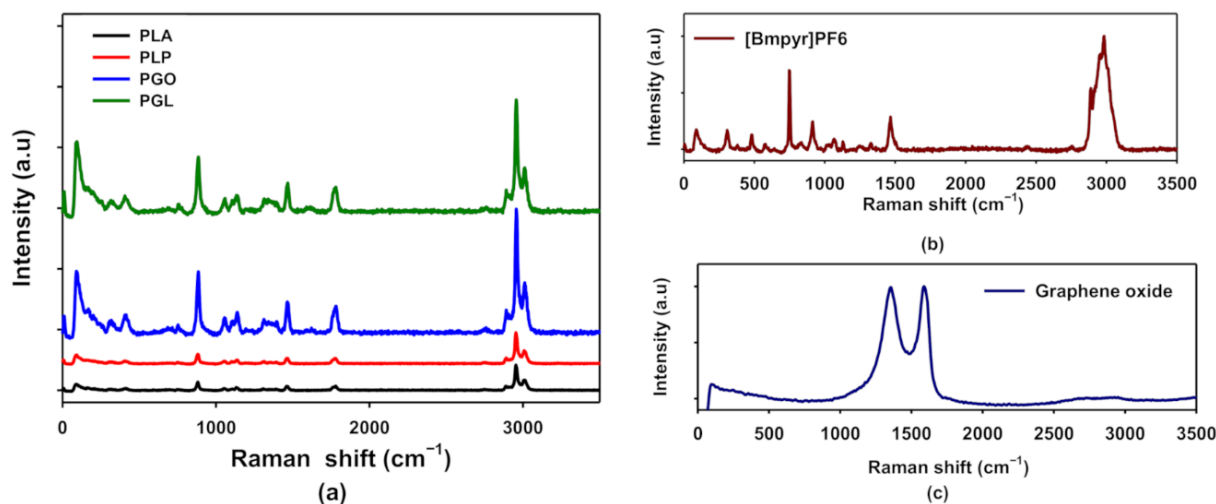


Figure 10. Raman spectra of: (a) PLA, PLP, PGO, and PGL; (b) [Bmpyr]PF₆; and (c) graphene oxide [Reproduced from [79], distributed under the terms and conditions of the CC BY license <https://creativecommons.org/licenses/by/4.0/>].

And finally, the study by D. Doganay et al. [68] also reported a uniform dispersion of Ag NWs even at high loadings, which was attributed to the presence of a thin residual polyvinylpyrrolidone (PVP) layer on the nanowire surface. They also demonstrated that, with an average alignment factor of 0.88, the spreading fabrication method encourages a high degree of alignment of Ag NWs along the processing direction. The presence of residual PVP in the PLA/Ag NW systems enabled the detection of an extra IR band at 2853 cm^{-1} . These results all converge on the conclusion that advanced structural characterization techniques such as SEM, XRD, Raman and FTIR are essential for correlating morphology, charge dispersion, and interfacial interactions with the resulting electrical and mechanical properties of PLA-based nanocomposites.

3.3. Mechanical Characterization

The incorporation of conductive fillers into PLA-based composites affects their mechanical behavior as well as improving their electrical properties. These properties are influenced by the type of filler used, its concentration, its morphology, and the processing method adopted. A carefully chosen concentration can provide significant mechanical reinforcement, while an excess or unsuitable dispersion can lead to a reduction in mechanical properties and increased material brittleness.

In this regard, research by Y. Wang et al. [80], L. Yang et al. [81] and M. M. Younus et al. [82] examined the effect of CNT fillers on the mechanical behavior of the PLA matrix. The results show that at moderate contents between 4 and 6 wt%, the tensile strength clearly improved, with a value reaching 68.5 MPa and a yield strength of 42 MPa at 6 wt%. Young's modulus also increased, approaching 1.92 GPa, while the elongation at break maintained a moderate level around 4.25%, reporting a balanced stiffness-ductility. Furthermore, at lower loadings, between 2 and 4 wt%, a mechanical improvement is generally observed, although the behavior changes depending on the manufacturing method. For example, melt blending tends to stiffen the matrix while compromising its ductility. While

the casting solution showed a loss of ductility, with tensile strength reaching 72 MPa at 0.5 wt% CNTs, it maintained high strength and enhanced elongation to around 24.4%, suggesting the excellent dispersion of CNTs and high compatibility with the PLA matrix.

According to the studies of Cheong et al. and S. Giner-Grau et al. [67,71], GNPs have a different dynamic. At low loading, between 1 and 3 wt%, they slightly improve the mechanical strength and, especially, the rigidity of the matrix, as approved by a modulus that can reach 4.25 GPa. However, above 7 wt%, the trend is reversed. Mechanical performance decreases significantly, probably due to less homogeneous dispersion and agglomeration of fillers, as demonstrated by the reduction in strength to 27 MPa at 12 wt%. This behavior highlights the importance of carefully dosing this type of filler to avoid negative effects.

The mastery of hybrid composite manufacturing also helps to achieve good compromise, as highlighted by G. S. P. Kumar et al. [83] in their study: the hybrid combination of 1.5 wt% CNT + 0.5 wt% GNP reported a strength of 48 MPa and a modulus of 4 GPa, reflecting a synergistic effect at low concentration.

As for carbon black (CB), its effect is highly dependent on loading in the PLA matrix. At 5–10 wt%, PLA/CB composites show strengths of between 31 and 37.5 MPa, with a maximum elongation around ~5% and a modulus reaching 1060 MPa [71]. In this range, these results indicate good dispersion and optimum mechanical percolation. However, above 12 wt%, mechanical performance stabilizes or even deteriorates slightly [84]. At 16–20 wt.%, strength drops to ~38 MPa, while elongation falls below 3%, showing that excess CB leads to a stiffer structure with reduced ductility. The main findings from the literature concerning the mechanical properties of conductive PLA composites are summarized in Table 3.

As a result, fine-tuning of filler content and homogeneous dispersion are a key factor in adjusting the mechanical performance of PLA-based composites according to the requirements and field of application of these innovative materials.

Table 3. Comparative summary of literature on mechanical characterization of conductive composites with PLA matrix.

Composites (PLA/Fillers)	Filler Content	Tensile Strength	Yield Strength (MPa)	Elongation at Break (%)	Young Modulus	Method	Refs
PLA/CNT + Graphène	0.5 wt% CNT + 0.5 wt% Graphene	35 MPa	~22 MPa	0.8%	~3 GPa	FDM	[83]
	1.0 wt% CNT + 0.5 wt% Graphene	42 MPa	~25 MPa	0.7%	~3.5 GPa	FDM	
	1.5 wt% CNT + 0.5 wt% Graphène	48 MPa	~28 MPa	0.5%	~4 GPa	FDM	
PLA/CNC/CNT	4.3 wt% CNT	45.52 MPa	~45.52 MPa	2.5%	~3.152 GPa	Pickering emulsions	[85]
PLA/GNP	1 wt% GNP	~43 MPa	-	~4.05%	~4.1 GPa	Melt blending	[67]
	3 wt% GNP	~47 MPa	-	~3.4%	~4.25 GPa		
	7 wt% GNP	~36 MPa	-	~3.7%	~3.35 GPa		
	12 wt% GNP	~27 MPa	-	~3.9%	~3.3 GPa		
PLA/CNTs	5.6 wt% CNT	~71.4 MPa	~35 MPa	~1.75%	~1.53 E (Young Modulus of neat PLA)	Melt blending	[80]

PLA/CNTs	2 wt% CNT	~48 MPa	~26 MPa	~5.5%	~1.27 GPa	Melt blending	[81]
	4 wt% CNT	~56 MPa	~35 MPa	~4.3%	~1.65 GPa		
	6 wt% CNT	~68.5 MPa	~42 MPa	~4.25%	~1.92 GPa		
PLA/GNPs	5 wt% GNP	~37 MPa	-	~1.5%	~875 MPa	3D print- ing	[71]
	10 wt% GNP	~27 MPa	-	~1.7%	~1100 MPa		
PLA/CB	5 wt% CB	~37.5 MPa	-	~3.75%	~875 MPa	Injection Molding	[82]
	10 wt% CB	~31 MPa	-	~5%	~1060 MPa		
PLA/GNPs	5 wt% GNP	~34 MPa	-	~5%	~750 MPa	Injection Molding	[84]
	10 wt% GNP	~30 MPa	-	~4.87%	~825 MPa		
PLA/CB	5 wt% CB	~38 MPa	-	~9.75%	~760 MPa		
	10 wt% CB	~33 MPa	-	~11.25%	~900 MPa		
PLA/CNTs	0.5 wt% CNTs	~72.2 MPa	-	~24.4%	~3.9 GPa	Solution casting	[82]
	1 wt% CNTs	~72 MPa	-	~30.3%	~3.86 GPa		
	3 wt% CNTs	~64 MPa	-	~51.8%	~3.3 GPa		
	5 wt% CNTs	~66.2 MPa	-	~42.7%	~3.19 GPa		
PLA/CB	4 wt% CB	~54 MPa	-	~5.3%	-	Melt- com- pounding	[84]
	8 wt% CB	~60 MPa	-	~5.1%	-		
	12 wt% CB	~63.5 MPa	-	~4.8%	-		
	16 wt% CB	~43 MPa	-	~3.2%	-		
	20 wt% CB	~38 MPa	-	~2.9%	-		

3.4. Electrical Characterization

Table 4 shows a literature comparison of the electrical properties of PLA-based composites, depending on the type of conductive filler, the filler content, and the manufacturing method used. In this context, Y. Wang et al. [80] have significantly improved the electrical conductivity of PLA/CNT composites using a two-stage dispersion strategy combining Pickering emulsion and a masterbatch process. The findings demonstrate an impressive conductivity of 72.2 S/m with a 5.6 wt% CNT content. PLA/CNTs and PLA/GNPs composites electrical performance has also been assessed by P. Lamberti et al. [86] for 3D printing. The CNTs achieved a reduced percolation threshold from 1.5 wt% to 3 wt%, with a conductivity reaching 4.54 S/m at 12 wt%. In contrast, the GNPs provide the best performance, with conductivity reaching 6.27 S/m at 12 wt%.

In the same context, G. Spinelli et al. [87] have provided further insight into PLA nanocomposites reinforced with MWCNTs, GNPs, and hybrid fillers (1:1) for 3D printing applications. Particularly, PLA/GNP composites require a higher load to initiate percolation, from 3 wt% to 6 wt%. PLA/(MWCNTs + GNPs) hybrid systems, on the other hand, percolate at around 3 wt% and reach 0.95 S/m at 12 wt%. These differences in performance are mainly attributed to the different aspect ratios of the fillers and their state of dispersion in the matrix.

In further research, Zeranska-Chudek et al. [88] studied PLA/GNP composites for thermal management and electromagnetic shielding (EMI) applications, giving special attention to the impacts of filler content and graphene nanoplatelet lateral size. The lateral dimensions of the GNPs used in the study were 0.2, 5, and 25 μm . The results achieved using 25 μm GNPs revealed a non-linear, exponential ratio between charge loading and electrical conductivity, underlining the effectiveness of this size in forming interconnected conductive networks. At 5 wt%, conductivity reaches around 0.1 S/m, while at 10 wt% an exponential increase is observed, with values exceeding several tens of S/m and peaking at around 116 S/m at 15 wt%. These results underline the fact that the combined optimization of GNP content and lateral size, in particular the use of 25 μm GNP, represents a

powerful strategy for significantly improving the electrical performance of PLA-based composites.

Finally, another study by J. Guo et al. [84] highlights the effect of CB on the electrical properties of PLA-based composites. The results reveal a progressive increase in conductivity reaching 0.125 S/cm at 8 wt%, with a tendency to stabilize thereafter. This stagnation indicates that the addition of extra charge no longer brings any significant improvement in electrical performance.

Table 4. State of the art on the electrical properties of PLA-based polymer composites at different loadings of CNTs, GNPs, MWCNTs, CB, and MWCNT + GNP hybrids (DC regime).

Composites (PLA/Fillers)	Filler Content	Conductivity	Resistivity	Refs
PLA/CNTs	12 wt% CNTs	4.54 S/m	0.22 Ohm.m	[86]
PLA/GNPs	12 wt% GNPs	6.27 S/m	0.159 Ohm.m	
PLA/CNTs	5.6 wt% CNT	72.2 S/m	1.38×10^{-2} Ohm.m	[80]
PLA/GNPs	5 wt% GNPs	10 S/m	1.00×10^{-1} Ohm.m	[88]
	10 wt% GNPs	16 S/m	6.25×10^{-2} Ohm.m	
	15 wt% GNPs	116 S/m	8.62×10^{-3} Ohm.m	
PLA/GNPs	1.5 wt% GNPs	1.5×10^{-12} S/m	6.67×10^{11} Ohm.m	[87]
	3 wt% GNPs	1.7×10^{-12} S/m	5.88×10^{11} Ohm.m	
	6 wt% GNPs	3.12×10^{-2} S/m	3.21×10^1 Ohm.m	
	9 wt% GNPs	3.47×10^{-1} S/m	2.88 Ohm.m	
PLA/MWCNTs	1.5 wt% MWCNTs	1.08×10^{-8} S/m	9.26×10^7 Ohm.m	
	3 wt% MWCNTs	1.4×10^{-2} S/m	7.14×10^1 Ohm.m	
	6 wt% MWCNTs	6.57×10^{-1} S/m	1.52 Ohm.m	
	9 wt% MWCNTs	9.4×10^{-1} S/m	1.06 Ohm.m	
PLA/(MWCNTs + GNPs)	1.5 wt% MWCNTs + 1.5 wt% GNPs	2.70×10^{-1} S/m	3.7 Ohm.m	[84]
	3 wt% MWCNTs + 3 wt% GNPs	3.52×10^{-1} S/m	2.84 Ohm.m	
	6 wt% MWCNTs + 6 wt% GNPs	5.33×10^{-1} S/m	1.88 Ohm.m	
PLA/CB	4 wt% CB	0.6 S/m	1.67 Ohm.m	[84]
	8 wt% CB	12.5 S/m	8×10^{-2} Ohm.m	
	12 wt% CB	13.5 S/m	7.4×10^{-2} Ohm.m	
	16 wt% CB	13.8 S/m	7.25×10^{-2} Ohm.m	
	20 wt% CB	14.3 S/m	6.99×10^{-2} Ohm.m	

4. Applications of PLA-Based Electrically Conductive Composites

Nowadays, the growth of electronic waste has created a serious environmental pollution problem on a global scale. However, growing awareness of environmental issues has encouraged the exploration of alternative materials to replace traditional ones. As a result, the use of biopolymer composites such as PLA has become a highly appropriate solution in various industrial sectors. Figure 11 represents the main fields of application for PLA-based conductive composites in the 3D printing industry, which are divided into four broad functional categories [89]. Notably the biomedical industry, to produce biocompatible electrodes, conductor supports, drug delivery systems, and biosensors [90]. They also offer promising prospects for the development of reliable, reproducible, and cost-effective 3D-printed synthetic scaffolds for tissue engineering and regenerative medicine [91]. For example, work using pure PLA or PLA/GNPs has shown improved cell

differentiation [92], while others have demonstrated improved bone regeneration using PLA/GNPs composites [93] or the use of PLA combined with calcium phosphate (CaP) and graphene oxide (GO) for bone applications [94].

In the energy field, these composites are used to improve the interfacial conductivity and electrochemical performance of 3D-printed PLA/GNP current collectors [95]. They are also being used to optimize PLA/CB-based electrodes to increase the efficiency of electrochemical storage devices. Furthermore, another study has developed a scalable and cost-effective method for supercapacitor fabrication, incorporating 3D-printed PLA/GNPs electrodes with tungsten disulfide (WS_2) deposition to enhance energy storage [96]. Such examples highlight that PLA-based composites can be directly printed into current collectors, supercapacitor electrodes [97], and other electrochemical devices for energy applications [98].

Also, in the field of electronics, several studies have been carried out to compare and optimize different activation processes for 3D-printed electrodes based on PLA-graphene (PLA-G) in order to significantly improve their electrochemical properties and develop high-performance sensors for the detection and quantification of molecular targets, notably dopamine [99]. Other researchers have developed planar resistance temperature detectors (P-RTD) using PLA/CB-based dual-nozzle FDM 3D printing, demonstrating the versatility of these materials for embedded sensors [100]. Therefore, beyond general future prospects, PLA-based composites have already been converted into actual 3D-printed devices, such as chemical sensors and integrated heat detectors.

Finally, in the field of electromagnetic shielding (EMI/ESD), many studies have explored the utilization of 3D-printed PLA/CB composites to improve protection against electromagnetic interference [101–103]. Meanwhile, others have developed composites based on PLA/PCL/MWCNT (multi-wall carbon nanotubes) with both good mechanical properties and high EMI shielding power [104]. These structures are converted to a conductive material via a silver-sprayed coating (AgNWs), opening the road to hybrid shielding and cooling solutions in advanced electronic systems [105]. These advances clearly demonstrate that PLA composites are not only being studied for their protective effectiveness, but are also being used in structures such as honeycomb panels and lightweight functional components.

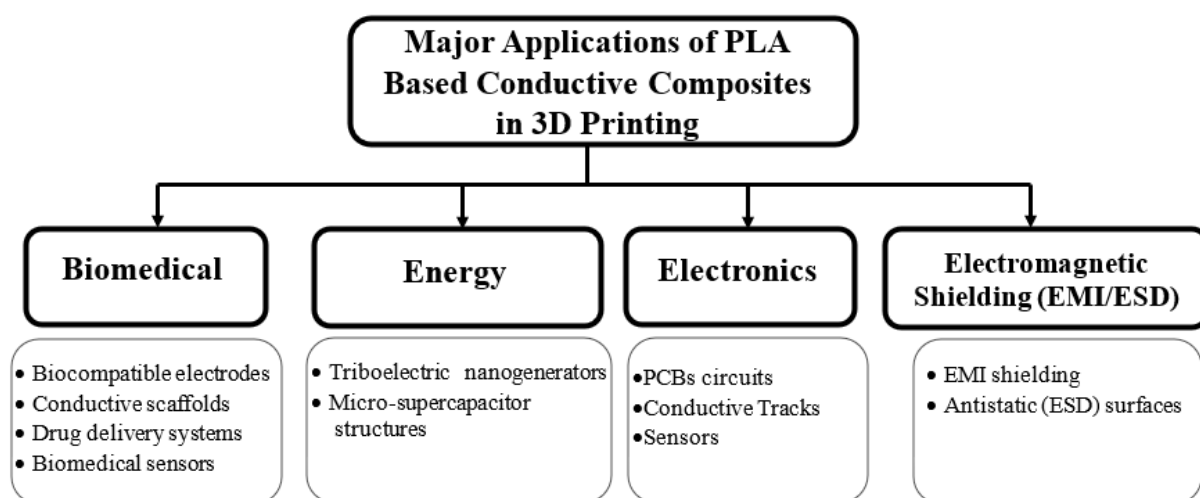


Figure 11. Major industrial applications of electrically conductive PLA-based composites.

5. Conclusions

The growing demand for environmentally friendly materials has sparked an increased interest in PLA as a biodegradable polymer matrix for conductive composites.

This review provides an overview of fundamental thermoplastics, with a particular focus on PLA as a bio-based matrix, and examines the conductive fillers frequently incorporated into the pure PLA matrix. Such fillers include carbon black (CB), carbon nanotubes (CNTs), graphene nanoplatelets (GNPs), silver nanowires (Ag NWs), and other emerging fillers, whose percolation thresholds have been studied to better understand their comparative performance in establishing conductive pathways within the polymer matrix. Carbon nanotubes are particularly noteworthy as specific fillers. Certain fillers, particularly carbon nanotubes and silver nanowires, achieve significant electrical conductivity at very low concentrations due to their elongated structure and high aspect ratio. In contrast, fillers such as carbon black or graphene require high concentrations to reach the percolation threshold, which can influence the mechanical and electrical properties of the composite. Such differences underscore the critical importance of selecting the right type of filler to achieve the desired performance, especially when the goal is to balance conductivity, lightness, and biodegradability in PLA-based systems.

This review also revealed significant differences in the mechanical and electrical performance of PLA-based composites, depending on the type of filler used, its content in the matrix, as well as the manufacturing method adopted. However, hybrid formulations, combining several types of fillers, appear particularly promising for reconciling high conductivity and structural stability, by exploiting synergistic effects. Nevertheless, several challenges persist: the addition of conductive fillers complicates recycling and can reduce the biodegradability of PLA, raising questions about life cycle and environmental trade-offs. From an industrial standpoint, process scalability, the still high cost of certain conductive nanomaterials, and the lack of standardized testing methods represent significant barriers. These aspects will need to be further explored in order to ensure the reproducibility and sustainability of results. Furthermore, a detailed understanding of the relationships between structure and properties remains a key challenge. Advanced characterization techniques, such as SEM, TEM, XRD, and FTIR spectroscopy, provide valuable information on morphology, charge dispersion, and interfacial interactions, which should be further exploited in future work. In this context, PLA-based conductive composites confirm their strong potential for the development of functional and sustainable materials suitable for a wide range of applications, from flexible electronics to electromagnetic shielding devices, provided that future research focuses on overcoming these obstacles.

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