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Polylactic acid (PLA)-based multifunctional and biodegradable nanocomposites and their applications

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ABSTRACT

Polylactic acid (PLA)-based nanocomposites are emerging as multifunctional, biodegradable materials, offering sustainable alternatives to petroleum-based plastics. This review examines recent advancements in PLA nanocomposites, focusing on enhanced mechanical strength, thermal stability, and biodegradability achieved through nanofillers like metallic particles, carbon-based materials, and ceramics. Techniques such as in situ polymerization, melt mixing, and electrospinning enable application-specific improvements. PLA's limitations, including brittleness and low barrier properties, are addressed to support diverse applications: in packaging (e.g., extended shelf life), biomedicine (e.g., degradable implants), and electronics (e.g., flexible devices). Despite challenges with filler dispersion and thermal resistance, continued innovations expand PLA's potential across multiple industries, contributing to a sustainable, circular economy.

Abbreviation	Full Form
PLA	Polylactic Acid
PET	Polyethylene Terephthalate
PS	Polystyrene
PHA	Polyhydroxyalkanoates
PBS	Polybutylene Succinate
CNT	Carbon Nanotube
SWCNT	Single-Walled Carbon Nanotube
MWCNT	Multi-Walled Carbon Nanotube
CNF	Cellulose Nanofiber
CNC	Cellulose Nanocrystal
BNC	Bacterial Nanocellulose
NC	Nanocellulose
HAp	Hydroxyapatite
nHAp	Nano-Hydroxyapatite
AgNP	Silver Nanoparticle
CuNP	Copper Nanoparticle
AuNP	Gold Nanoparticle
ZnO	Zinc Oxide
TiO_2	Titanium Dioxide
MgO	Magnesium Oxide
OMMT	Organically Modified Montmorillonite
HNT	Halloysite Nanotubes
BG	Bioactive Glass
PEG	Polyethylene Glycol
PPG	Polypropylene Glycol
GNP	Graphite Nanoplatelet
GNS	Graphite Nanosheet
rGO	Reduced Graphene Oxide
DCNP	Dye-Clay Hybrid Nanoparticles
MDI	Methylene Diphenyl Diisocyanate
TMSA	Octadecyl Trimethyl Ammonium Chloride
HDTA	Hexadecyl Trimethyl Ammonium Bromide
SEM	Scanning Electron Microscopy
TEM	Transmission Electron Microscopy
XRD	X-ray Diffraction
DSC	Differential Scanning Calorimetry

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ALP	Alkaline Phosphatase
BIC	Bone–Implant Contact
MTX	Mitoxantrone
CQD	Carbon Quantum Dot
FFF	Fused Filament Fabrication
OLED	Organic Light-Emitting Diode
UCNP	Upconversion Nanoparticle
CB	Carbon Black
MAO	Micro-Arc Oxidation
BRS	Bioresorbable Scaffold

1. Introduction

The widespread reliance on synthetic, petroleum-based materials in daily life has led to significant environmental concerns, including CO_2 emissions, non-biodegradable waste, and reduced soil fertility [1–3]. While recycling and reuse efforts exist, they are often cost-prohibitive, limiting their feasibility in many regions [4]. These concerns have spurred industrial and academic shifts toward "green materials"—biodegradable, biopolymer-based alternatives derived from natural resources. Unlike conventional plastics, biopolymers are produced from renewable sources, require less manufacturing energy, and decompose naturally, supporting global initiatives to reduce plastic waste and mitigate climate change [5–7]. Biobased polymers, categorized into those synthesized from monomers, microbial fermentation, or modified natural substances offer promising substitutes across biomedical, agricultural, and household applications [5,8–10]. Recent studies have explored advanced strategies to enhance the multifunctionality of biopolymer-based nanocomposites. For instance, Wu et al. demonstrated the synergistic effect of hybrid GNP/CNT networks on the mechanical and electrical performance of PLA nanocomposites [11], while Ci et al. reported highly stretchable and conductive cellulose-TPU systems tailored for wearable electronics [12]. Electroconductive hydrogels have also emerged as promising candidates for biomedical applications due to their combined toughness, elasticity, and bio-adhesion [13]. Winnacker's recent review [14] further underscores the growing interest in biopolymer fibers driven by the need for sustainable and high-performance materials. However, challenges like lower mechanical strength and production limitations remain. Ongoing research aims to improve biopolymer performance through co-blending and plasticizer use [15,16].

Polylactic acid (PLA) is a biodegradable, thermoplastic polyester derived from renewable resources like corn starch, sugarcane, and cassava roots [17,18]. As an eco-friendly alternative to petroleum-based plastics, PLA is valued for its lower carbon footprint and ability to decompose into non-toxic components under industrial composting [19]. PLA's good tensile strength and modulus are comparable to conventional polymers such as polystyrene (PS) and polyethylene terephthalate (PET). However, its brittleness, low impact resistance, and limited thermal stability restrict its use in high-demand applications [20,21]. PLA is often combined with fillers and reinforcements, including natural fibers, inorganic nanoparticles, and other polymers to overcome these limitations. It forms composites that enhance its mechanical, thermal, and barrier properties while retaining biodegradability [22,23]. Fig. 1 illustrates the PLA nanocomposite production process from raw materials to applications.

The demand for multifunctional materials—those that provide multiple functional properties in a single material—has grown to meet increasingly diverse performance requirements [25]. Multifunctional materials, which combine properties like durability, thermal stability, and environmental resistance, simplify product design and manufacturing, reduce material usage, and lower production costs. They offer particular advantages in space- and weight-sensitive fields like aerospace and automotive [26]. In biomedical applications, for example, multifunctional materials that combine mechanical robustness, biocompatibility, and antimicrobial properties streamline device design, enhancing patient outcomes and reducing infection risks [27]. Beyond conventional enhancements, recent innovations have enabled multifunctional PLA-based systems capable of energy harvesting (e.g., triboelectric nanogenerators) [28], thermal and electromagnetic shielding [29], and simultaneous mechanical and electrical performance optimization via hybrid nanofillers [11,30,31]. These advances highlight the versatile potential of PLA-based nanocomposites across various demanding applications.

Environmental concerns and the shift toward sustainability drive demand for biodegradable materials. Conventional plastics made from fossil fuels persist in the environment for centuries, polluting ecosystems and posing risks to wildlife and human health [1,2]. In contrast,

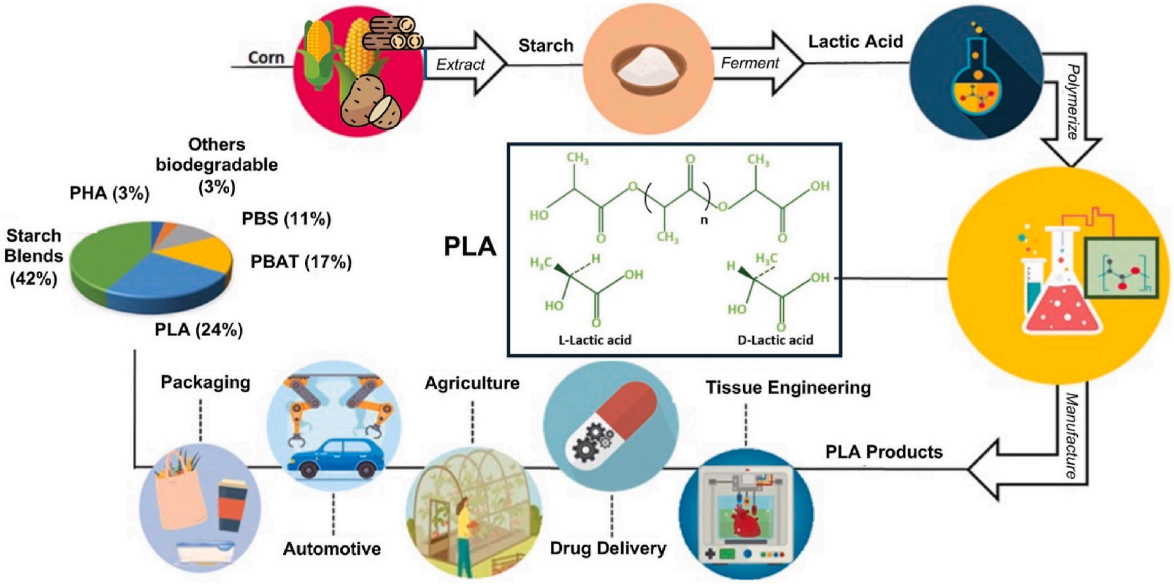

Fig. 1. Production and Applications of Polylactic acid (PLA) [24]. PLA is produced from renewable agricultural biomass, such as corn, sugarcane, and cassava. It has three different types: amorphous PLA, semi-crystalline PLA, and highly crystalline PLA. PLA-based products find applications in various fields, including packaging, biomedical devices, electronics, and other industrial uses.

biodegradable materials like PLA break down under natural conditions, helping mitigate environmental impact and promote ecological balance [18]. PLA's renewable sourcing and biodegradability make it a promising material for sustainable applications [32]. PLA-based nanocomposites combine biodegradability and multifunctionality, expanding their potential across industries and supporting global sustainability goals.

Integrating multifunctionality and biodegradability in PLA-based nanocomposites marks a notable advancement in materials science. These composites enhance barrier properties against gases and moisture in packaging, extend the shelf life of perishable goods, and remain compostable after use [6,33]. In biomedicine, PLA-based nanocomposites offer biocompatibility, controlled degradation, and antimicrobial properties, reducing healthcare costs and improving patient outcomes [34–36]. In electronics, conductive PLA-based nanocomposites are used in flexible electronics and sensors, combining conductivity with environmental sustainability [37,38]. Tailoring PLA properties through the inclusion of nanomaterials enables customized solutions across diverse applications [23]. PLA-based multifunctional nanocomposites thus represent a valuable resource in the transition toward sustainable and innovative material solutions.

To ensure a comprehensive literature review, a systematic search was conducted using available databases (Web of Science, Scopus, and Google Scholar). The selection focused on peer-reviewed articles published primarily within the past five years, with inclusion criteria emphasizing novelty, experimental rigor, and relevance to the multifunctionality, sustainability, and practical implementation of PLA-based nanocomposites. Foundational and highly cited studies were also included to provide essential context. While numerous reviews have addressed aspects of PLA nanocomposites [23,36,37,39–45], this work provides a unified and integrative overview focused on multifunctionality—specifically mechanical reinforcement, thermal stability, electrical conductivity, bioactivity, and barrier properties—within the context of scalable and sustainable fabrication techniques. Moreover, this review distinguishes itself by systematically examining how different synthesis approaches—melt mixing, in situ polymerization, solution casting, electrospinning, and additive manufacturing—affect nanofiller dispersion, interfacial interactions, and composite performance. By linking material design principles to application-oriented challenges in packaging, biomedical engineering, and flexible electronics, this review highlights the transformative potential of PLA-based nanocomposites and provides critical insights to guide future research and industrial development.

2. Fundamentals of PLA and nanomaterials

2.1. Properties of polylactic acid (PLA)

Polylactic acid (PLA) is known for its impressive mechanical strength and modulus, comparable to conventional polymers like polyethylene terephthalate (PET) and polystyrene (PS), with tensile strengths of 50–70 MPa and Young's moduli between 2.7 and 16 GPa, depending on processing conditions [17,20]. Its transparency and biocompatibility make it suitable for biomedical uses, including sutures, implants, and drug delivery. PLA's thermoplastic properties allow for conventional processing methods like injection molding, extrusion, and 3D printing, expanding its industrial applications [19,21]. PLA exists in three stereoisomeric forms: levorotatory (L-), dextrorotatory (D-), and meso (a blend of L- and D-), which influence its physical characteristics and degradation rate. Higher molecular weight reduces crystallinity but increases tensile strength and viscosity due to chain entanglement, while stereochemistry affects whether PLA is semicrystalline or amorphous based on the D/L ratio [46–49]. This adaptability in PLA's structure allows customization for various applications.

However, PLA has limitations, including brittleness (2–10 % elongation at break) and limited thermal stability (glass transition temperature of 55–75 °C and melting point of 140–210 °C), restricting its use in high-impact and high-temperature applications [22,42]. PLA's hydrolytic degradation is advantageous in medical and packaging applications, where biodegradability is desired. To enhance its performance, PLA is often modified with other polymers, plasticizers, and nanoparticles, which improve its thermal stability, impact resistance, and barrier properties while maintaining biodegradability [6,45]. PLA-based nanocomposites show strong biodegradability under composting, hydrolytic, or enzymatic conditions. The degradation process begins with water absorption, followed by bacterial action on oligomer fragments. The type and concentration of nanofillers, like nano clays and cellulose nanocrystals, can influence PLA's degradation, with carbon nanotubes either promoting or hindering the process based on their stability and impact on barrier properties [7].

To contextualize PLA's performance among biodegradable polymers, it is essential to compare its key properties with those of polyhydroxyalkanoates (PHA), polybutylene succinate (PBS), and starch-based plastics. PLA exhibits high tensile strength, good thermal resistance, and favorable processability—especially for melt processing and 3D printing applications. However, its brittleness (i.e., low elongation at break) and moderate biodegradation rate can limit its broader adoption [50]. PHA offers excellent ductility and biodegradability but is hindered by high production costs and limited commercial scalability [51]. PBS demonstrates mechanical toughness and thermal stability but has not achieved widespread industrial penetration [52]. Starch-based plastics are low-cost and highly biodegradable, yet they suffer from poor moisture resistance and mechanical strength [53]. The comparative insights are summarized in Table 1.

2.2. Nanoparticles/nanofillers for PLA-based composites

This section examines the nanoparticles (NPs) and nanofillers commonly used in PLA-based nanocomposites. Advances in nanotechnology have enabled the production of nanostructured materials (typically under 100 nm), offering properties distinct from bulk materials and suited for various applications [58]. Nanomaterials, both organic and inorganic, are used in PLA-based nanocomposites based on the required properties. Nanomaterials are classified by dimensionality, Fig. 2A: 0-D (e.g., quantum dots), 1-D (e.g., nanowires), 2-D (e.g., graphene sheets), and complex 3-D materials (e.g., cellular microstructures) [59]. In PLA nanocomposites, nanoparticles are broadly categorized into metallic (e.g., silver), carbon-based (e.g., carbon nanotubes), ceramic (e.g., hydroxyapatite), and natural fillers (e.g., cellulose nanocrystals). Fig. 2A provides a classification of nanomaterials, while Fig. 2D displays electron microscopy images of typical nanofillers like silver nanoparticles, carbon nanotubes, carbon nanofibers, hydroxyapatite, cellulose

Table 1
Comparative properties of PLA and other biodegradable polymers [51,54–57].

Property	PLA	PHA	PBS	Starch-Based
Tensile Strength (MPa)	50–70	20–40	30–45	3–30
Elongation at Break (%)	2–10	30–300	50–300	10–60
Thermal Stability (°C)	Up to 160	Up to 180	Up to 200	Below 150
Processability	High (extrusion, 3D printing)	Moderate	High (injection molding, film blowing)	Low (often blended)
Biodegradability Rate	Moderate	High	High	Very High
Production Cost ($/kg)	2–3	4–15	4.5	1.5–2.0
Industrial Scalability	High	Low–Moderate	Moderate	Moderate

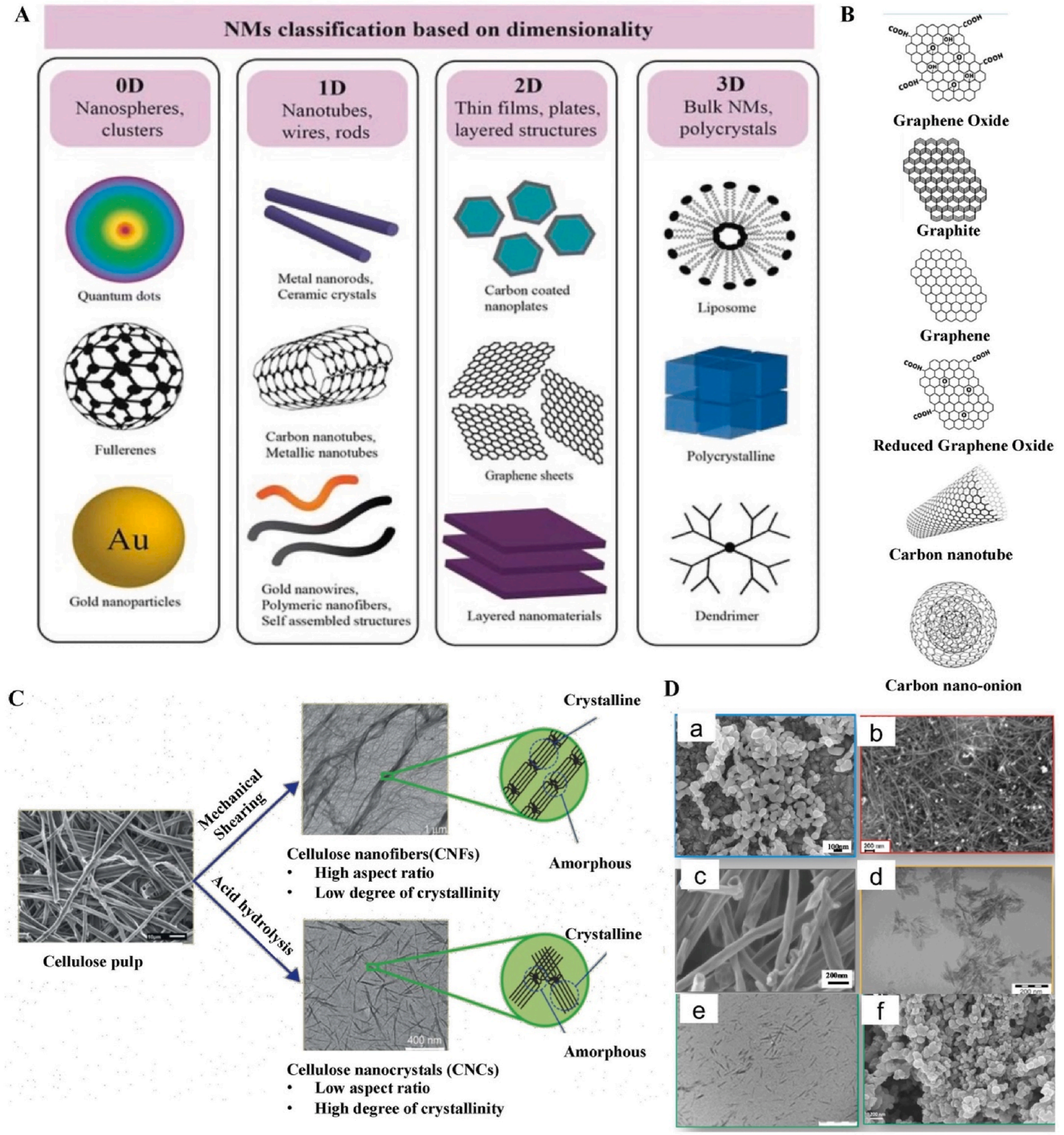

Fig. 2. Types of Nanomaterials and Nanofillers. (A) Diagram illustrating the classification of nanomaterials (NMs) based on dimensionality [59]. (B) Structural forms of commonly used graphene-based nanomaterials [60]. (C) Production process of cellulose nanofibers (CNFs) and cellulose nanocrystals (CNCs) derived from cellulose pulp. [61–64]. (D) Electron microscopy images of primary nanofillers used in PLA-based nanocomposites: (a) silver nanoparticles, (b) single-walled carbon nanotubes, (c) carbon nanofibers, (d) nanohydroxyapatite, (e) cellulose nanocrystals, and (f) lignin nanoparticles [7,65].

nanocrystals, and nano lignin. Each type of nanofiller offers specific enhancements to PLA-based nanocomposites, such as increased mechanical strength, thermal stability, and barrier properties, tailoring the material for diverse applications.

2.2.1. *Metallic nanoparticles*

Metallic nanoparticles (MNPs) significantly enhance PLA-based nanocomposites by imparting antibacterial, mechanical, and thermal improvements. MNPs are typically classified into pure metals (e.g., silver (Ag), gold (Au), copper (Cu)) and metal oxides (e.g., ZnO, MgO, TiO_2). Silver nanoparticles (AgNPs) are well-researched for their unique optical, electronic, catalytic, and antimicrobial properties, making them suitable for applications in catalysis, biosensing, drug delivery, and medical devices. AgNPs possess a high surface area and surface atom fraction, which enhances their antibacterial activity [23,66]. Copper nanoparticles (CuNPs) are valued for their antimicrobial and antifungal properties, contributing to improved electrical conductivity and mechanical strength in PLA/Cu composites, thus ideal for food packaging and medical devices to combat resistant bacteria [67,68]. Gold nanoparticles (AuNPs), recognized for their stability and biocompatibility, are used in drug delivery, tissue engineering, and medical devices, where they improve the thermal and mechanical properties of PLA nanocomposites [69]. Zinc oxide (ZnO) nanoparticles provide UV-blocking and antibacterial benefits, enhancing PLA's tensile strength and making it ideal for packaging and outdoor applications [70]. Titanium dioxide (TiO_2), known for its photostability and UV resistance, is commonly used in PLA for surface sterilization in packaging and medical devices [71]. Magnesium oxide (MgO), an environmentally friendly, non-toxic material recognized as GRAS by the FDA [1], is used in antibacterial PLA composites for bone regeneration and cancer treatment applications [72,73]. In recent studies, Zirconium dioxide (ZrO_2) nanoparticles have been shown to enhance thermal stability and rigidity of PLA nanocomposites processed via material extrusion (MEX) [74].

2.2.2. *Carbon nanostructures*

Carbon-based nanostructures, including carbon nanotubes (CNTs), carbon nanofibers (CNFs), graphene, and fullerenes, offer significant mechanical, electrical, and thermal enhancements to PLA nanocomposites (Fig. 2B). CNTs, available as single-walled (SWCNTs) and multi-walled (MWCNTs), are highly conductive and mechanically robust, making them ideal for electronic applications where improved crystallization and conductivity are required. CNTs' high aspect ratio and stability also enhance PLA's thermal resistance, benefiting multifunctional devices [75–78]. Graphene, with its high surface area and two-dimensional structure, improves PLA's mechanical strength, flexibility, and thermal and electrical conductivity, making it ideal for applications requiring durability and resistance to wear. Graphite nanoplatelets (GNPs) and graphite nanosheets (GNS) also contribute to dimensional stability, resistance to micro-cracking, and barrier properties in PLA [78,79]. Carbon nanofibers (CNFs), offering elasticity and strength like CNTs at a lower cost, and fullerenes, which enhance structural and thermal stability, further expand the utility of PLA in high-performance applications [23].

2.2.3. *Ceramic nanoparticles*

Ceramic nanoparticles, produced by combining non-metal and metalloid elements under heat and pressure, are valued for their mechanical strength, stability, and bioactivity, making them ideal for biomedical applications. Bioactive glasses (BG), composed of low-silica ceramics, are widely used for bone repair and prosthetic implants due to their ability to form hydroxyapatite, which promotes bone adhesion and biocompatibility. When combined with PLA, bioactive glasses improve composite bioactivity, making them suitable for implants and drug delivery [80,81]. Hydroxyapatite (HAp), a bioactive ceramic derived from natural or synthetic sources, is osteoconductive and osteoinductive, facilitating bone regeneration in PLA composites for tissue engineering applications [82,83]. Nano clays, composed of layered mineral silicates, are used in PLA nanocomposites to improve mechanical properties, though high concentrations may reduce effectiveness due to compatibility issues. Common nano clays include organic montmorillonite (OMMT), bentonite, and halloysite nanotubes (HNTs), which enhance barrier properties, thermal stability, and stiffness [84–87]. Similarly, alumina (Al_2O_3) nanoparticles have shown excellent potential in reinforcing PLA matrices. For instance, PLA/Al_2O_3 nanocomposites produced via MEX 3D printing exhibited significantly improved tensile, flexural, and impact strength, demonstrating their suitability for structural and high-impact applications [88]. Besides conventional ceramic nanofillers, metallic carbides like tungsten carbide (WC) have also demonstrated similar reinforcement behavior. For example, WC-reinforced PLA composites fabricated via MEX, improved rheological, morphological, and thermomechanical performance [89].

2.2.4. *PLA nanocomposites with natural nanofillers*

Natural nanofillers such as nanocellulose (NC), lignin, and tannins improve PLA's mechanical, thermal, and environmental properties, making it a more sustainable choice. NC, derived from cellulose fibers, is renewable and biodegradable, with a low carbon footprint, Fig. 2C. It improves the barrier, mechanical, and thermal properties of PLA, making it suitable for packaging, textiles, and medical applications. NC exists in three main forms: cellulose nanocrystals (CNCs), cellulose nanofibrils (CNFs), and bacterial nanocellulose (BNC), each offering unique structural benefits. Comparatively, CNFs improve strength and ductility due to their flexible structure and hydrogen bonding. At the same time, CNTs improve stiffness with limited elongation, highlighting the need to tailor filler selection to specific mechanical requirements. NC films can be recycled and reprocessed, aligning well with sustainable packaging needs [85,90,91]. Lignin, the second most abundant natural polymer, is used in biofuels, polymers, adhesives, and carbon fibers. Its aromatic structure enhances PLA's mechanical properties, though achieving optimal dispersion can be challenging. Strategies to improve lignin distribution in PLA aim to maximize its benefits as a sustainable filler [92,93].

In summary, while the individual advantages of metallic, carbon-based, ceramic, and bio-derived nanofillers are discussed in detail in subsequent sections, their selection is fundamentally driven by the intended functional goals. Metallic nanofillers are primarily selected for their antimicrobial and electrical properties, making them suitable for biomedical and sensing applications. Carbon-based nanomaterials offer superior mechanical reinforcement and conductivity, ideal for structural and electronic functions. Ceramic fillers enhance bioactivity and thermal resistance, supporting tissue engineering and high-temperature applications. Natural and biodegradable nanofillers contribute to sustainability, aligning with green material design for packaging and environmental use. This application-guided approach ensures that each nanofiller type is effectively tailored to achieve multifunctionality in PLA-based composites.

3. Synthesis of PLA-based nanocomposites

PLA nanocomposites are synthesized primarily through in situ polymerization, solution casting, and melt mixing, with additional methods such as electrospinning and additive manufacturing. These methods facilitate the integration of various nano-additives into the PLA matrix to enhance its properties. Fig. 3 provides an overview of these preparation methods.

3.1. *In situ polymerization*

In situ polymerization is a prevalent method for synthesizing PLA-based nanocomposites due to its ability to achieve uniform nanofiller dispersion within the polymer matrix. In this technique, nanoparticles are introduced to the monomer or low-molecular-weight oligomers of PLA before the polymerization reaction begins, allowing nanofillers to be distributed evenly as the polymer chains form. This approach promotes covalent bonding between the nanoparticles and the PLA matrix, enhancing mechanical, thermal, and barrier properties [46,49]. In situ polymerization also supports nanoparticle exfoliation and prevents agglomeration, even at higher concentrations of nanofillers, leading to improved interparticle spacing [23,39].

For example, a study involving sepiolite nanoclay incorporated into PLA via in situ polymerization showed improved thermal stability and a higher melting point, due to uniform filler dispersion [94]. Yang et al. [95] used thermally reduced graphene oxide (TRG) as an initiator with poly(L-lactide) (PLLA) through in situ ring-opening polymerization, demonstrating a strong interaction between TRG sheets and PLLA chains. This interaction resulted in a stable structure and improved

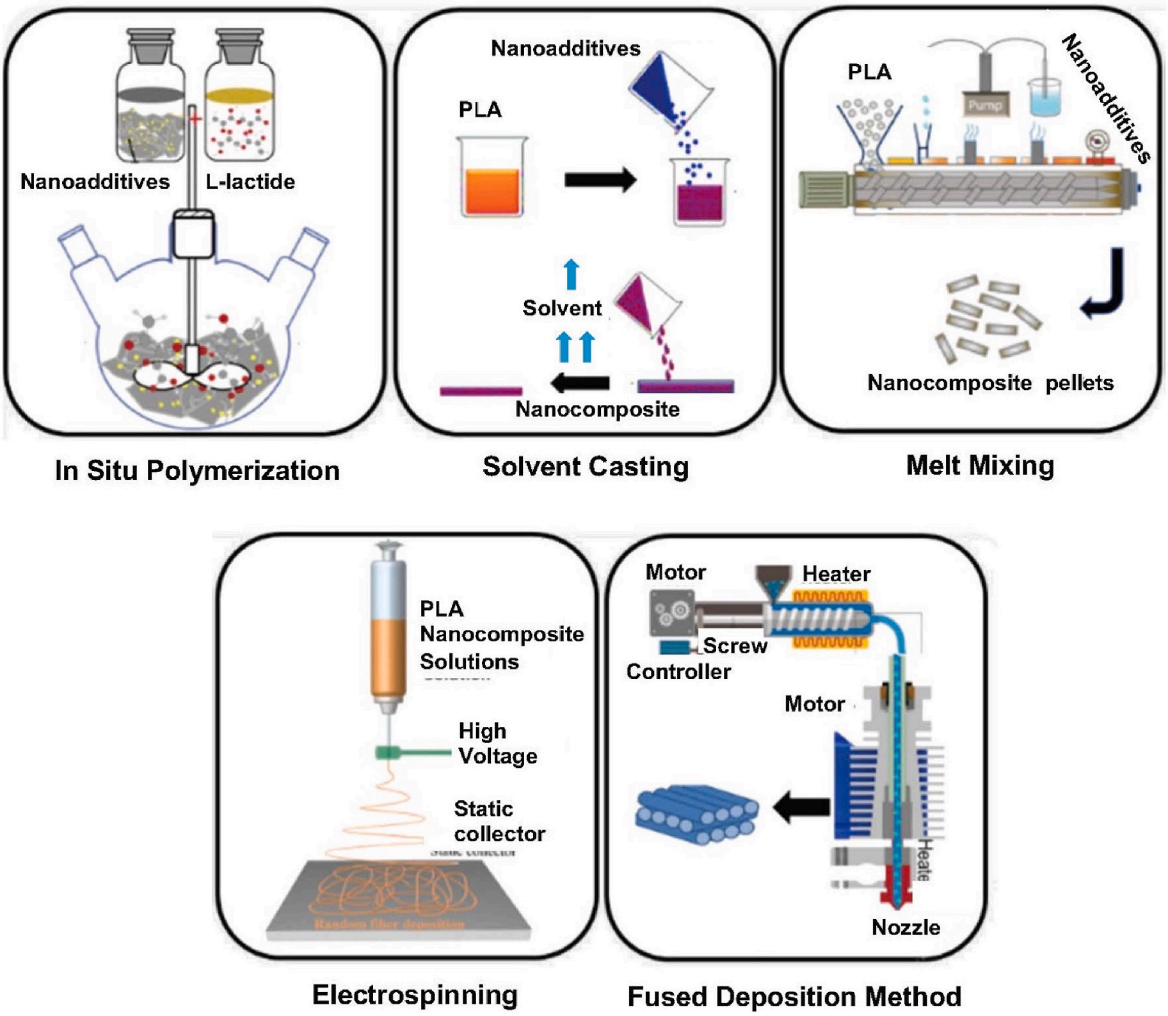

Fig. 3. Methods Used for the Preparation of PLA Nanocomposites [23]. Illustration of various techniques employed for preparing PLA nanocomposites, including in situ polymerization, solvent casting, melt mixing, electrospinning, and fused deposition modeling.

material properties. Such studies highlight in situ polymerization's capacity to achieve high-performance nanocomposites suitable for advanced applications.

Achieving uniform nanofiller dispersion within the PLA matrix is critical in situ polymerization, as it directly affects composite performance. To evaluate dispersion quality, several complementary characterization techniques are employed. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) offer high-resolution imaging to visualize filler distribution and morphology [96]. X-ray diffraction (XRD) is particularly useful for layered silicates, revealing intercalation or exfoliation behavior by changes in basal spacing [46,97]. Rheological analysis provides indirect yet sensitive insight by capturing modifications in viscoelastic properties, which correlate with network formation and filler interactions [98]. Differential scanning calorimetry (DSC) helps to assess crystallinity and thermal transitions, which may be influenced by filler distribution and nucleation effects [99]. The integration of these techniques enables a robust, multi-scale understanding of nanofiller dispersion in situ polymerized PLA nanocomposites.

3.2. *Solution casting*

Solution casting is a widely utilized technique for PLA-based nanocomposites, especially when producing films and coatings. This process involves dissolving PLA in a solvent containing dispersed nanofillers. Upon solvent removal, a composite film is formed with a uniform distribution of the nanofiller. Solution casting offers simplicity and control over the dispersion of nanofillers, making it suitable for applications requiring precision in thin-film production. However, the method's reliance on organic solvents raises potential risks for polymer contamination and limits its scalability.

One study using solution casting to create PLA/TiO_2 nanocomposites involved dissolving PLA in chloroform while dispersing TiO_2 in ethanol. The resulting nanocomposite displayed enhanced tensile strength, reduced water vapor transmission rates, and improved water resistance due to the uniform distribution of TiO_2 particles [100]. Another example is the use of citric acid-modified nano clay in PLA, where the modified clay was incorporated to create a shape memory nanocomposite. The interaction between the ester groups of PLA and citric acid limited the chain mobility, aiding shape recovery and improving compatibility within the matrix [101]. While solution casting is widely used at the laboratory scale due to its simplicity and ability to produce uniform films, it presents notable environmental drawbacks. Chief among these are the reliance on volatile organic solvents and the associated need for energy-intensive solvent recovery and disposal processes [102]. In contrast, methods such as melt mixing and in situ polymerization are solvent-free, offering greener and more scalable alternatives. Although these methods may require elevated temperatures or chemical initiators, they significantly reduce environmental impact and are more suitable for industrial-scale production [103]. Thus, the ecological footprint of solution casting remains a key limitation when evaluating sustainable manufacturing routes.

3.3. Melt mixing

Melt mixing, also known as melt blending, is a common method for producing PLA-based nanocomposites. It involves heating PLA above its melting point and applying shear forces to incorporate nanofillers. This technique is advantageous for bulk production as it requires no solvents, reducing environmental impact and production costs, and is compatible with standard industrial equipment such as twin-screw extruders, injection molders, and extruders [49,104]. Melt mixing is suitable for large-scale production, especially in applications like packaging and automotive parts, where the method's efficiency outweighs some of its limitations.

Despite its advantages, the high temperatures and shear forces used in melt mixing may induce thermal degradation in PLA, potentially affecting its mechanical properties. Nevertheless, the method has proven effective in achieving good nanofiller dispersion for certain PLA nanocomposites. For example, PLA/organically modified montmorillonite (OMMT) composites prepared using a twin-screw extruder showed improved tensile properties at 3 %, 5 %, and 7 % nano clay loadings [46]. However, when graphene is used as a nanofiller, it can lead to agglomeration challenges. Functionalizing graphene enhances its compatibility with PLA, which improves both dispersion and mechanical properties. Murariu et al. demonstrated successful PLA nanocomposites with functionalized expanded graphite, leading to increased rigidity and modulus, suitable for high-performance applications [105].

3.4. Electrospinning

Electrospinning is a highly effective technique for producing PLA-based nanocomposite fibers with diameters ranging from nanoscale to submicron levels. These fibers offer significant advantages for applications in textiles, medical products, and food packaging. This method uses an electric field to draw a polymer solution or melt from a needle, creating thin, continuous fibers as the solvent evaporates or the melt cools. Electrospinning enables the development of multifunctional fibers, providing a higher surface area-to-volume ratio and greater flexibility compared to microscale fibers produced by traditional methods like melt spinning [38].

PLA/HNT nanocomposite fibers produced via electrospinning exhibited diameters in the range of 230–280 nm, offering enhanced strength and functionality [106]. PLA/CNC fibers, with diameters as small as 405–642 nm, improved the composite's mechanical properties and demonstrated potential for filtration and packaging applications [107]. Additional studies showed successful synthesis of PLA/graphene oxide (GO) and PLA/nanohydroxyapatite (nHAp) fibers using electrospinning, resulting in average fiber diameters of 563 × 196 nm and 412 × 240 nm, respectively, with enhanced antimicrobial and UV-blocking properties [108–111]. These findings underscore electrospinning's versatility in producing PLA nanocomposite fibers for advanced applications, although achieving uniform dispersion within the matrix can remain challenging.

3.5. Additive manufacturing

Additive manufacturing (AM), specifically MEX has gained traction as a promising technique for PLA-based nanocomposites. MEX allows for the 3D printing of PLA composites into complex geometries, layer by layer, with minimal material waste. This method enables customization of nanocomposite shapes and sizes, offering versatility for biomedical, electronics, and automotive applications [17,112]. The optimal MEX printing temperature for PLA is around 215 °C, which enhances the material's mechanical properties during printing [23].

PLA/nHAp composites have been successfully 3D printed for medical applications, providing controllable properties and stable structures. However, issues arise with extrusion at high filler content (above 50 %), which can impede smooth nozzle flow [113]. Kumar et al. [114] demonstrated the uniform dispersion of CNFs in PLA using MEX, with a 3 % CNF content resulting in a 23.3 % improvement in tensile strength. Similarly, PLA/CNT composites showed a 64.12 % increase in tensile strength and a 29.29 % increase in flexural strength with 6 wt% CNT. Additionally, 3D-printed PLA-G electrodes exhibited enhanced electrochemical performance, making them suitable for molecular sensing applications [115]. Although most studies focus on inorganic nanofillers, some work has explored polymeric reinforcements in PLA. For instance, PTFE nanoparticles were used as a reinforcement agent to improve the mechanical properties and dimensional accuracy of PLA parts fabricated via MEX, offering a solid-lubricant effect and enhanced interlayer bonding [116]. These examples highlight additive manufacturing's potential to produce functional PLA-based nanocomposites with advanced properties.

Each synthesis technique for PLA-based nanocomposites presents inherent trade-offs that must be carefully considered. In situ polymerization enables superior nanofiller dispersion and interfacial bonding but typically involves complex chemistries, longer processing times, and potential residual catalysts that may impact biocompatibility. Melt blending is widely adopted for its scalability and solvent-free processing; however, the high viscosity of PLA and strong filler-filler interactions can result in poor dispersion and mechanical degradation. Solution casting allows for good filler dispersion under controlled conditions but suffers from low scalability and environmental concerns due to solvent toxicity and disposal requirements. Electrospinning offers excellent control over nanofiber morphology for biomedical applications, yet the method has limited throughput and may require post-treatment for uniformity. Additive manufacturing provides customization and rapid prototyping benefits, but challenges remain in integrating nanofillers uniformly and maintaining rheological stability of the printing feedstock. These considerations highlight the importance of aligning synthesis techniques with the specific performance, environmental, and scalability requirements of the target application.

4. Various applications of PLA-based nanocomposites

The rising demand for PLA-based nanocomposites is largely attributed to their promising applications across key sectors such as food packaging, biomedical, and electronics. As discussed, the properties of PLA can be precisely modified using various nanomaterials, enhancing its performance for specialized uses. This adaptability has led to a growing interest in PLA nanocomposites, which are now increasingly utilized across multiple industries. This section examines their role in advancing performance, functionality, and application versatility.

4.1. PLA-based nanocomposites for packaging applications

PLA has become a widely used material in the packaging industry, particularly for food packaging, as researchers continue to explore sustainable alternatives to petroleum-based polymers. This "green polymer" plays a crucial role due to its biocompatibility and robust physical properties, including high strength, thermoplasticity, processability, and non-toxicity, all of which are valuable in food packaging. However, PLA's inherent limitations-such as limited flexibility, weak crystallization, and poor barrier properties-restrict its use. To enhance its performance, PLA is often combined with nanofillers and active additives, improving mechanical strength, thermal and chemical stability, water vapor and gas barrier properties, recyclability, biodegradability, optical qualities, antifungal, and antimicrobial activities [7,117]. Table 2 provides a comprehensive overview of PLA-based nanocomposites developed for packaging applications, detailing the types of nanofillers, fabrication techniques, and their impact on mechanical strength, barrier properties, and biodegradability.

Table 2
PLA-based nanocomposites for packaging applications.

Nanofiller Type	Synthesis Method	Key Enhancements	Limitations	References
MCC + AgNPs	Twin-screw extrusion + injection molding	Strong antibacterial activity, ↑ degradation, ↑ transparency	Possible silver toxicity, filler cost	[118]
CNC + AgNPs	Melt extrusion	↑ Tensile modulus, ↑ antibacterial activity	Acid hydrolysis complexity, cost of AgNPs	[119]
PLA + NC (carrot pomace) + AgNPs	Solution mixing + melt compounding	↑ Strain at break, ↑ antibacterial activity, ↑ hydrophilicity	↑ Oxygen permeability	[120]
PLA + Tonsil®, Aerosil®, Sorbitan oleate	Melt extrusion	Enhanced mechanical strength, flexibility, liquid resistance (Sorbitan oleate)	Moisture sensitivity (Tonsil®), trade-offs in barrier strength	[121]
PLA + DCNP	Solution casting	↑ Storage modulus, ↑ T_g, 36 % ↓ O_2 permeability, UV protection	DCNP aggregation at high loading reduces performance	[122]
PLA + Cu-modified MMT	Melt extrusion	Improved elongation, thermal stability, and antimicrobial activity	CuO caused agglomeration, color change, and brittleness	[123]
NCC + chitin whiskers + MDI	Melt extrusion + compatibilizer	↑ Tensile strength, ↓ OTR, ↓ WVP	Matrix defects at higher MDI levels	[124]
Organoclay (HDTA, TMSA)	Extrusion vs. injection molding	↑ Dispersion in extrusion, ↓ Agglomeration, ↑ Suitability for cosmetic packaging	Injection molding Tactoids ($\geq$45 μm), heterogeneous dispersion	[125]
Nano-lignin + CNF	Melt blending	↑ UV protection, ↑ Tensile strength, ↑ Barrier properties	↑ Brittleness, ↓ Transparency	[126]
CNF + AgNPs	Solution casting + AgNP spraying	↑ Young's modulus, ↓ WVP, ↑ Antibacterial activity, Safe migration limits	Performance influenced by Ag content	[127]
Lignin nanoparticles + Ci	Melt extrusion + supercritical impregnation	↑ UV-light barrier, ↑ biodegradability ↑ thermal & mechanical properties, non-toxic (in vivo)	Color change; requires SCF processing	[128]
Cuprous oxide (Cu_2O) + CNF	3D printing with thermomechanical processing	↑ Tensile strength, ↑ Flexural strength, strong antibacterial activity against *S. aureus* and *E. coli*	Study focused on lab-scale; long-term stability not evaluated	[129]
PLA-coated mica nanosheets (Nano-mica/PLA)	PLA-assisted exfoliation and shear-force assembly	↑ Mechanical strength, ↑ UV shielding, ↑ Gas barrier properties	Complexity of structure, mineral source dependency	[130]
MgO	Melt extrusion and blown film processing	↑ Tensile strength, ↑ Plasticity, ↑ Oxygen & WVTR barrier, Antibacterial (*E. coli*)	Optimal improvements at low wt%, scalability beyond not tested	[131]
ZnO nanorods, TiO_2	Solution casting with pre-synthesized ZnO nanorods	↑ Mechanical strength, ↑ UV absorption, ↑ Hydrolytic degradation, ↑ Antibacterial activity	Aggregation at >5 wt%; combined fillers ↓ mechanical strength	[132]

One approach to enhancing PLA-based nanocomposites' multifunctionality is through the use of microcrystalline cellulose (MCC) and AgNPs to improve mechanical, antibacterial, and degradation properties [118]. Using twin-screw extrusion and injection molding, researchers achieved a uniform dispersion of MCC and Ag within the PLA matrix. The addition of 5 wt% MCC increased the tensile modulus by 26 %, thereby reinforcing PLA's mechanical strength, while 1 wt% AgNPs introduced robust antibacterial effects against *E. coli* and *S. aureus*, with greater inhibition of *E. coli* due to silver's impact on bacterial respiration. Disintegration tests under composting conditions showed that MCC accelerated PLA degradation, with 75 % disintegration achieved within 21 days while maintaining optical transparency. In a related study [119], CNCs were used instead of MCC to create multifunctional films for packaging and sanitary products. These CNCs, synthesized from MCC via sulfuric acid hydrolysis, were incorporated into PLA through melt extrusion, yielding films with an 83 % increase in tensile modulus and strong antibacterial activity at 1 wt% AgNPs.

The barrier and migration properties of these nanocomposites have also been investigated, revealing a 60 % reduction in oxygen transmission rate (OTR) and a 59 % decrease in water vapor permeability (WVP) compared to neat PLA, thus enhancing the material's potential for packaging. Migration tests confirmed that silver release remained below European Food Safety Authority (EFSA) limits for food contact materials, reinforcing these composites' safety for packaging applications [133]. PLA/nanocellulose composites derived from carrot pomace and embedded with AgNPs exhibited a 28 % increase in strain at break and demonstrated effective antibacterial activity against *E. coli* and *B. cereus* [120]. However, the high hydrophilicity and elevated oxygen permeability of these composites limit their suitability for high-barrier packaging, highlighting the need for further modifications to enhance barrier performance.

To address potential toxicity concerns with certain nanomaterials, bio-based alternatives such as Tonsil® clay, Aerosil® silica, and Sorbitan oleate have been explored as viable fillers. Melt-extruded PLA composites containing these additives exhibited diverse performance profiles: Tonsil® provided flexibility and mechanical stability, while Aerosil® composites demonstrated the highest tensile strength (22 MPa) due to uniform particle dispersion. Although the Tonsil®-based composites exhibited increased water absorption, impacting barrier properties, the Sorbitan oleate-based variant showed strong resistance to liquid penetration. Overall, these bio-based fillers enhance PLA's mechanical performance, but they present unique trade-offs in barrier and moisture retention [121]. The incorporation of hybrid nano-pigments into PLA, such as dye-clay hybrid nanoparticles (DCNP), into PLA has been shown to enhance both mechanical properties and UV shielding. As illustrated in Fig. 4A, the films were fabricated via solution casting. At an optimal loading of 3 wt% DCNP, the storage modulus and glass transition temperature increased, while oxygen permeability decreased by 36 %, indicating strong potential for UV-sensitive food packaging applications. However, higher DCNP concentrations led to nanoparticle aggregation, which adversely affected both mechanical strength and barrier performance [122]. Another approach demonstrated by Bruna et al. that incorporating copper-modified montmorillonite into PLA films significantly improved antibacterial activity and barrier properties. This dual enhancement positions the composite as a strong candidate for active food packaging applications requiring microbial safety and structural integrity [123].

In sustainable packaging, Gond et al. [134] developed PLA-based films with nanocellulose derived from sugarcane bagasse, achieving a significant increase in tensile strength (35 MPa) and optimal crystallinity at 2 wt% due to uniform dispersion and hydrogen bonding. These films demonstrated a 15 % reduction in oxygen permeability. Fig. 4B shows the hydrophobic nature of the films with various nanocellulose loadings, which increase with cellulose content, but decrease beyond 4 wt% due to the crystalline nature of nanocellulose, which contributes to wettability. However, at higher nanocellulose concentrations, film transparency decreased, and water absorption increased. Kumar [135] reported a 393 % increase in tensile strength in PLA/CNF nanocomposite films using CNFs extracted from jute, alongside improved thermal stability and a 33 % reduction in water vapor permeability

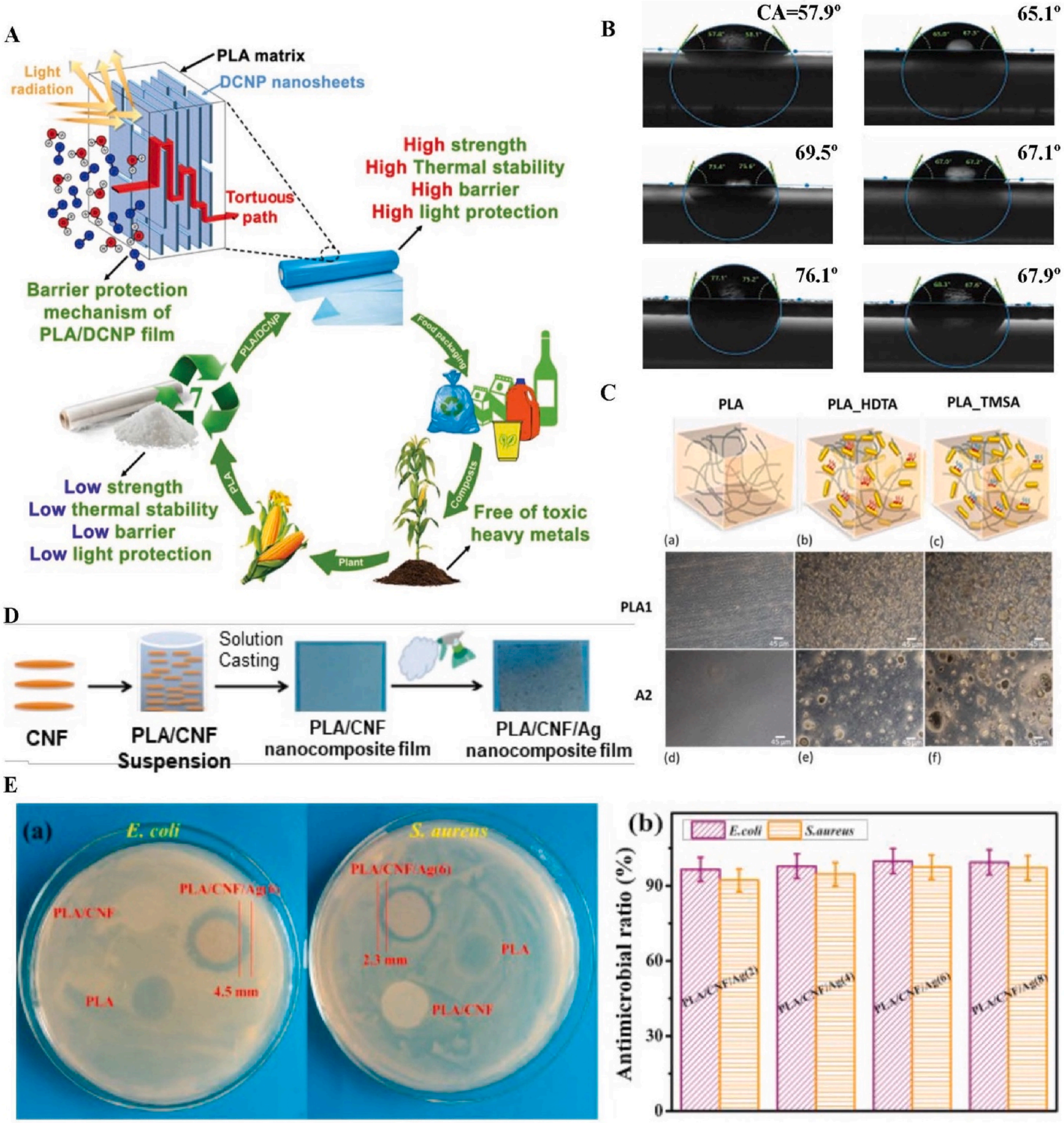

Fig. 4. PLA-Based Nanocomposites for Packaging Applications. (A) Preparation and application of PLA/DCNP nanocomposite films by solution casting [122]. (B) Contact angle images of PLA-based nanocomposite films with varying nanocellulose content, showing changes in hydrophobicity [134]. (C) Schematic and optical images of PLA and PLA-clay nanocomposites with HDTA- and TMSA-modified organoclays (4 wt%) [125]. Grey lines represent the polymer chain phase, yellow blocks represent the clay reinforcing phase with HDTA (red tail and head group) or TMSA (blue tail and red head group) organic modifications. The processing techniques influenced clay dispersion, with extruded samples (PLA1) showing uniform dispersion of HDTA and TMSA organoclays (b–c), while injection-molded samples (PLA2) exhibited a heterogeneous distribution with large clay tactoids (≥45 μm) due to agglomeration (e–f). (D) Fabrication process of PLA/CNF/Ag nanocomposite films using a spraying method to deposit AgNPs [127]. (E) Antibacterial properties of PLA/CNF/Ag(6) nanocomposite films against *E. coli* and *S. aureus* (a), and the antimicrobial ratios (b) of the films at varying Ag contents [127]. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

(WVP). Further research explored melt-extruded PLA bio-nanocomposites reinforced with both nanocrystalline cellulose (NCC) and chitin whiskers (CHW), achieving a 41 % increase in tensile strength and a 15 % reduction in oxygen transmission rate (OTR). The addition of 4 wt% methylene diphenyl diisocyanate (MDI) as a compatibilizer further decreased WVP by 36 %. However, higher MDI content introduced matrix defects, indicating an optimal compatibilizer loading threshold [124]. Collectively, these studies underscore PLA's potential for high-barrier packaging applications when appropriately reinforced and compatibilized.

PLA-based nanocomposites incorporating clay fillers modified with hexadecyl trimethyl ammonium bromide (HDTA) and octadecyl trimethyl ammonium chloride (TMSA) have been developed and assessed for cosmetic packaging applications [125]. The study compared nanocomposites produced via extrusion (PLA1) and injection molding (PLA2), with a focus on organoclay dispersion (Fig. 4D). Results showed that processing technique significantly influenced filler distribution. In extruded PLA1 samples (Fig. 4D b–c), both HDTA and TMSA-modified clays were uniformly dispersed within the matrix. In contrast, injection-molded PLA2 samples (Fig. 4D e–f) exhibited poor dispersion, with large tactoids (≥45 μm) formed by agglomerated clay sheets. These findings demonstrate the advantage of extrusion processing in achieving homogeneous filler dispersion, thereby enhancing the suitability of PLA nanocomposites for high-performance cosmetic packaging.

PLA/lignin nanocomposites with cinnamaldehyde (Ci) offer UV protection and antimicrobial effects, achieving 90 % disintegration within 23 days in composting conditions. Nano-lignin specifically enhances UV-blocking and tensile strength, although higher lignin content increases brittleness and aggregation risks [128,136]. PLA/lignin composites with cellulose nanofibrils from recycled newspaper pulp show increased tensile strength and enhanced barrier properties, although lignin content may affect film transparency [126].

In studies investigating nanocellulose aspect ratios, Yu et al. compared cellulose nanospheres, nanocrystals (CNCs), and nanofibers (CNFs) in PLA composites [137]. CNCs significantly enhanced barrier properties, while CNFs, due to their higher aspect ratio and percolating network, provided the highest mechanical strength, achieving a 350 % increase in Young's modulus. Yu et al. also developed a multifunctional PLA nanocomposite incorporating CNCs and AgNPs (Fig. 4D) [127]. A novel spraying technique ensured uniform AgNP dispersion, enhancing the composite's antibacterial, mechanical, and barrier properties (Fig. 4E). The ternary PLA/CNF/Ag nanocomposites were prepared by solution casting, followed by spraying a silver ammonia aqueous solution onto the binary PLA/CNF films. Both the deposited AgNPs and CNFs acted as efficient reinforcements, improving the thermal, mechanical, and barrier properties, along with exhibiting significant antibacterial activity, which was influenced by Ag content. These findings suggest that the novel PLA/CNF/Ag nanocomposite films hold promising potential for advanced food packaging applications. In addition to single-filler approaches, recent studies have explored multifunctional PLA nanocomposites using binary inclusions. For example, Petousis et al. incorporated cuprous oxide (Cu_2O) and cellulose nanofibers into PLA via 3D printing, demonstrating a synergistic improvement in antibacterial properties and mechanical strength. This highlights the promise of dual-filler strategies for multifunctional biomedical and packaging applications [129].

Han et al. proposed a PLA-assisted exfoliation and dispersion method to prepare PLA-coated mica nanosheets (Nano-mica/PLA) derived from the natural mineral phlogopite (Fig. 5) [130]. By leveraging a shear force assembly, they fabricated nacre-inspired nanocomposite films with a "brick-and-mortar" structure. These films exhibited excellent mechanical properties, UV-shielding, and gas barrier performance, demonstrating great potential for practical packaging applications of PLA.

Among various nanofillers, metal oxides such as ZnO, MgO, TiO_2, and SiO_2 have gained attention for their superior antibacterial, optical, and UV-shielding properties [131]. For instance, Swaroop and Shukla developed blown PLA/MgO nanocomposite films using an industrial-scale melt-processing setup. Their study reported a nearly 22 % increase in tensile strength and a 146 % improvement in plasticity for 2 wt% MgO-reinforced films. Additionally, oxygen and water vapor barrier properties improved by approximately 65 % and 57 %,

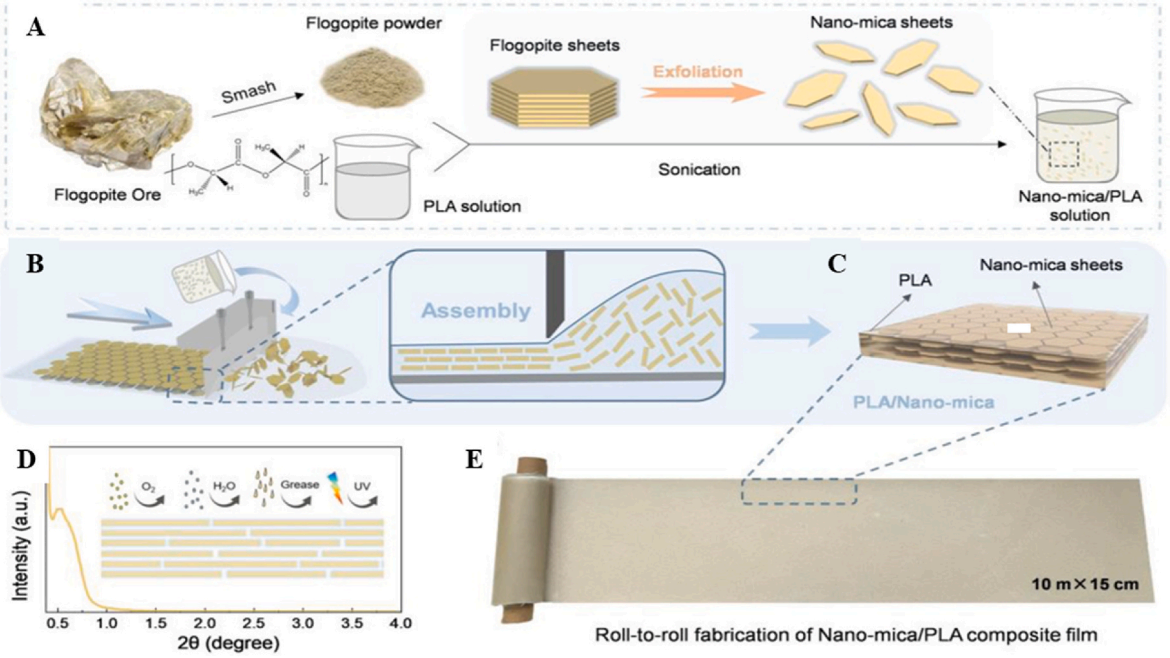

Fig. 5. PLA-Based Nanocomposites for Packaging Applications. (A) Exfoliation process of nano-mica sheets from natural phlogopite. (B) Shear force assembly process used to fabricate PLA-coated nano-mica sheets. (C) Diagram illustrating the "brick-and-mortar" configuration of nacre-inspired PLA/nano-mica films. (D) Small-angle XRD analysis of the structural organization of nano-mica sheets within the films. (E) Nacre-inspired films in rolled form, highlighting their potential for large-scale applications [130].

respectively, for the 1 wt% MgO formulation. Furthermore, the 1 wt% nanocomposite films demonstrated antibacterial efficacy, with around 44 % of *E. coli* bacteria killed after 24 h of treatment [131]. Similarly, Tajdari et al. showed that the synergistic incorporation of ZnO and TiO_2 nanoparticles into PLA enhanced UV protection, mechanical stability, and antibacterial behavior, making them suitable for sterilizable packaging and biomedical films [132]. Building on this concept, Dehghan et al. introduced GO-ZnO hybrids combined with *Mentha longifolia* essential oil into PLA matrices, achieving multifunctional films with notable antibacterial and antioxidant activity, alongside improved biodegradability-an approach well-suited for sustainable food packaging applications [138].

Despite these advancements, challenges remain in fully leveraging PLA nanocomposites for packaging. Achieving consistent dispersion of nanofillers to avoid agglomeration remains challenging, as does optimizing nanofiller loadings for improved properties without sacrificing flexibility. PLA's lower thermal stability limits applications involving high temperatures, and while its biodegradability is beneficial, it may impact the shelf life of acidic or high-moisture foods. Finally, limited barrier properties against gases, moisture, and oxygen persist, though nanofillers partially mitigate these issues. Overcoming these limitations is essential to unlock PLA nanocomposites' full potential in sustainable packaging solutions.

4.2. *PLA-based nanocomposites for biomedical applications*

PLA-based nanocomposites are emerging as promising materials in biomedical fields, particularly in tissue engineering, wound healing, and drug delivery, owing to their biocompatibility, biodegradability, and mechanical adaptability. For example, Kim et al. developed PLA/hydroxyapatite (HA) nanocomposite fibers via electrospinning, targeting bone regeneration applications [139]. The addition of HA to PLA enhances mechanical strength, biocompatibility, and osteo-conductivity, while the inclusion of hydroxy-steric acid (HAS) promotes homogeneous HA dispersion within the PLA matrix. The resulting fibrous scaffolds support bone cell growth and activity, as depicted in Fig. 6A, which shows the electrospinning setup used for fiber production. Given their compatibility with bone tissue, these scaffolds are suitable for both tissue engineering and drug delivery systems. Table 3 summarizes recent advances in PLA-based nanocomposites for biomedical applications, highlighting their nanofiller type, fabrication methods, biocompatibility, mechanical properties, and therapeutic potentials.

Rapacz-Kmita et al. created PLA-based nanocomposites with montmorillonite (MMT) fillers, resulting in multifunctional materials with antibacterial properties and controlled drug release capabilities [140]. Using solvent casting, they produced PLA/MMT films loaded with antibiotics like gentamicin and neomycin, which displayed clear zones of bacterial inhibition and sustained drug release, making these composites suitable for wound dressings and temporary implants (Fig. 6B). However, the faster degradation rate, due to weaker polymer-nanofiller interactions, limits these composites' long-term applications where durability is essential.

Another study by Injorhor et al. focused on PLA-PHA nanocomposites reinforced with nano-hydroxyapatite (nHAp) [141]. The addition of PHA enhances flexibility, while nHAp improves osteo-conductivity. Solution casting was used to prepare these

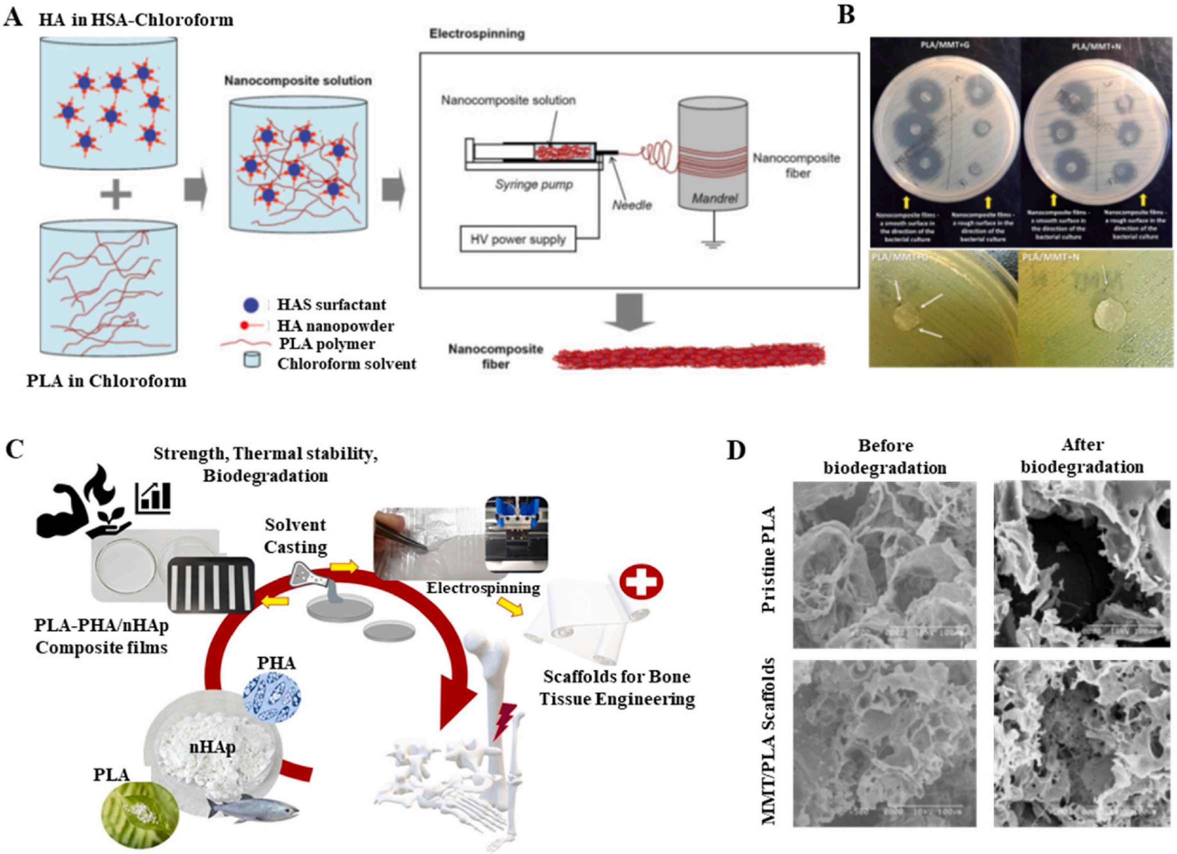

Fig. 6. PLA-Based Nanocomposites for Biomedical Applications. (A) Schematic of the experimental design for HA–PLA nanocomposite fibers supported by HSA surfactant, fabricated via electrospinning [139]. (B) Antibacterial activity of PLA/MMT + G and PLA/MMT + N nanocomposite films, shown (a) before and (b) after 6 weeks of degradation in distilled water [140]. (C) Preparation and potential applications of PLA-PHA/nHAp nanocomposite films, highlighting their suitability for biomedical use by solvent casting and electrospinning [141]. (D) SEM images of pristine PLA and MMT/PLA nanocomposite scaffolds, illustrating structural changes before and after biodegradation in water at 60 °C [143].

Table 3
PLA nanocomposites for biomedical applications.

Nanofiller Type	Synthesis Method	Key Enhancements	Limitations	References
HAp	Electrospinning with HSA surfactant	↑ Osteoconductivity, ↑biocompatibility, and uniform fiber formation	No in vivo data	[139]
MMT	Solution casting	↑Antibacterial activity, sustained drug release	Faster degradation, limited long-term use	[140]
PHA + nHAp	Solution casting and electrospinning	↑Osteoconductivity, ↑ thermal stability, ↑ in vitro degradation	Limited biological evaluation	[141]
HAP/ESNP + TiO_2@Mg	Solution casting	↑ Tensile strength, ↑ degradation rate, surface roughness, swelling, hydrophilicity	Complex fabrication steps	[142]
MMT	Electrospinning + cold compression + salt leaching/gas forming	↑ Dual porosity (nano + micro pores), ↑ scaffold integrity during degradation, ↑ pinhole formation for nutrient/waste transport	Complex multi-step fabrication	[143]
nHAp on Zn with MAO interlayer	Micro-arc oxidation (MAO) + sol-gel impregnation	↑ Corrosion resistance, ↑ osteoblast adhesion and proliferation, ↑ cytocompatibility	Specific mechanical data not provided	[144]
Al_2O_3 and SiO_2	Digital Light Processing (DLP) 3D printing	↑ Tensile strength and wear resistance, ↑ Strain in hybrid systems	↓ Tensile strength in silica-rich and hybrid systems	[145]
ZnO + Tranexamic Acid (TXA)	Electrospinning	↑ Antibacterial activity (E. coli, S. aureus), ↑ Hemostasis, ↑ Wound closure (90 % in 14 days), ↑ Cell attachment	Long-term biocompatibility and chronic wound efficacy not yet studied	[146]
MWCNTs + Doxorubicin (DOX)	Electrospinning	↑ NIR-triggered drug release, ↑ Local hyperthermia, ↑ Antitumor efficacy (chemo + photothermal), ↑ Porosity for cell binding	Requires NIR source, long-term safety not yet evaluated	[147]
TiO_2 + Daunorubicin	Electrospinning + drug self-assembly	↑ Drug loading efficiency, ↑ Targeted accumulation in leukemia cells, ↑ Surface area, ↑ Biocompatibility	Long-term stability and in vivo efficacy not evaluated	[148]
MWCNTs	Melt mixing + FFF	↑ Tensile strength, ↑ Thermal stability (up to 270 °C), ↑ Mild antibacterial properties	Electrical performance and biocompatibility require further validation	[149]
C60-phe-PLA + Mitoxantrone (MTX)	Self-assembly via dispersion-solvent diffusion	↑ Tumor-targeted drug delivery, ↑ Photodynamic therapy + chemotherapy, ↑ MTX retention in tumor, ↓ Systemic toxicity	Requires photodynamic irradiation, clinical validation needed	[150]
nHAp + Chitosan + Gelatin	Sol-gel method + Lyophilization	↑ Porosity, ↑ Thermal stability, ↑ Antibacterial resistance; ↓ Cytotoxicity	↓ Compressive strength, insufficient for compact bone	[151]
LA-Ta_2O_5/LA-HA	Melt Mixing	↑ Tensile strength & modulus; ↑ Nanofiller dispersion, strut thickness, ↓ Scaffold recoil	Long-term fatigue and in vivo performance not yet confirmed	[152]
nHAp	3D printing	↑ Printability, ↑ Tunable mechanical strength with n-HA content, ↑	In vivo evaluation limited to rabbit model	[113]

composites, which exhibited improved tensile strength, thermal stability, and biodegradability. Through electrospinning, these nanocomposites were converted into fibrous scaffolds that promote cell growth and bone repair (Fig. 6C). Osteoconductivity in PLA/nHAp composites is typically assessed using both in vitro and in vivo methods. In vitro, alkaline phosphatase (ALP) activity assays, calcium deposition analysis via Alizarin Red S staining, and osteoblast proliferation assays are commonly used to quantify early and late markers of osteogenesis. In vivo, the bone–implant contact (BIC) ratio and newly formed bone volume are frequently measured using micro-computed tomography (micro-CT) and histological analysis, providing quantitative evidence of osseointegration and bone regeneration [153,154]. These metrics are crucial for evaluating the biological functionality of PLA/nHAp systems in bone tissue engineering applications.

Bioceramic-filled PLA nanocomposites have also been investigated for orthopedic and maxillofacial implants. By incorporating hydroxyapatite, eggshell nanoparticles, and titanium dioxide-coated magnesium (TiO_2@Mg) into PLA, researchers enhanced the material's mechanical properties, hydrophilicity, and surface roughness, all of which are crucial for bone-related applications. However, managing magnesium's rapid degradation (which releases hydrogen gas) and TiO_2 agglomeration remains a challenge in achieving uniform, durable implants [142].

A related approach by Lee et al. involved developing poly(L-lactic acid) (PLLA)/MMT scaffolds with dual-porosity through electrospinning and salt leaching [143]. This dual-porosity promotes cellular activity, nutrient exchange, and faster bone regeneration (Fig. 6D). Meanwhile, micro-arc oxidation (MAO) combined with PLA/nHA coatings has shown promise in addressing implant stability, with Zn/MAO/PLA-nHA (7:3) composites displaying enhanced adhesion, corrosion resistance, and osteoblast growth [144]. Such materials offer a potential solution for bone implants, though in vivo studies are necessary to confirm clinical efficacy. In parallel, hybrid reinforcement of PLA with Al_2O_3 and SiO_2 nanoparticles via 3D printing has been shown to enhance flexural strength and dimensional precision, supporting its application in customized load-bearing biomedical components requiring both mechanical robustness and biodegradability [145].

In wound healing, novel PLA/ZnO nanofibrous composites loaded with tranexamic acid (TXA) have emerged as effective wound dressings. These electrospun nanofibers exhibited significant antibacterial effects against *E. coli* and *S. aureus*, and in vivo tests showed rapid hemostasis and 90 % wound closure within 14 days. The nanofibrous structure mimics the extracellular matrix, enhancing cell attachment and accelerating healing, making it highly suitable for wound management. However, longer-term studies are required to fully assess biocompatibility and chronic wound applications [146].

PLA nanocomposites have also been explored in drug delivery, particularly in cancer treatment. For instance, PLA/MWCNT composites loaded with the anticancer drug doxorubicin demonstrated controlled drug release when exposed to near-infrared (NIR) light. The MWCNTs generate localized heat under NIR irradiation, enhancing drug delivery and tumor reduction, showing potential for localized chemo- and photothermal therapies [147]. Additionally, PLA/nano-TiO_2 composites created through electrospinning showed improved drug loading and biocompatibility. These materials achieved increased drug accumulation in leukemia cells, underscoring their efficacy in targeted cancer treatment [148].

In the context of 3D printing, multifunctional PLA/MWCNT nanocomposites produced via melt mixing and fused filament fabrication (FFF) exhibited enhanced mechanical, thermal, and electrical properties. At just 1.0 wt% MWCNT loading, tensile strength increased by 34 % and the elastic modulus by 33 %, while thermogravimetric analysis indicated stability up to 270 °C. This composite's mild antibacterial properties further support its use in bioelectronics and medical devices, as 3D printing enables complex geometries and tailored designs for specific biomedical applications [149]. Researchers have also developed C60-PLA/Mitoxantrone (MTX) microspheres for targeted chemo-photodynamic therapy. Fullerene (C60) derivatives linked to PLA self-assemble into microspheres, achieving sustained drug release over 15 days. In vivo studies on tumor-bearing mice demonstrated a 93 % tumor suppression rate with reduced systemic toxicity, offering a localized approach to cancer treatment [150].

Scaffolds for bone tissue engineering have also benefited from PLA nanocomposites. Biodegradable PLA/nHAp scaffolds with a PLA/Gel/CHT matrix mimic natural bone structure, with an interconnected porous architecture that enhances osteo-conductivity and compressive strength. Varying nHAp concentrations yielded scaffolds with optimal pore sizes and mechanical stability, supporting cellular attachment for bone regeneration [151]. For orthopedic applications, PDLLA/PCL/BG nanocomposites were developed for ACL bio-screws, showing gradual degradation over six months, controlled bone formation, and minimal

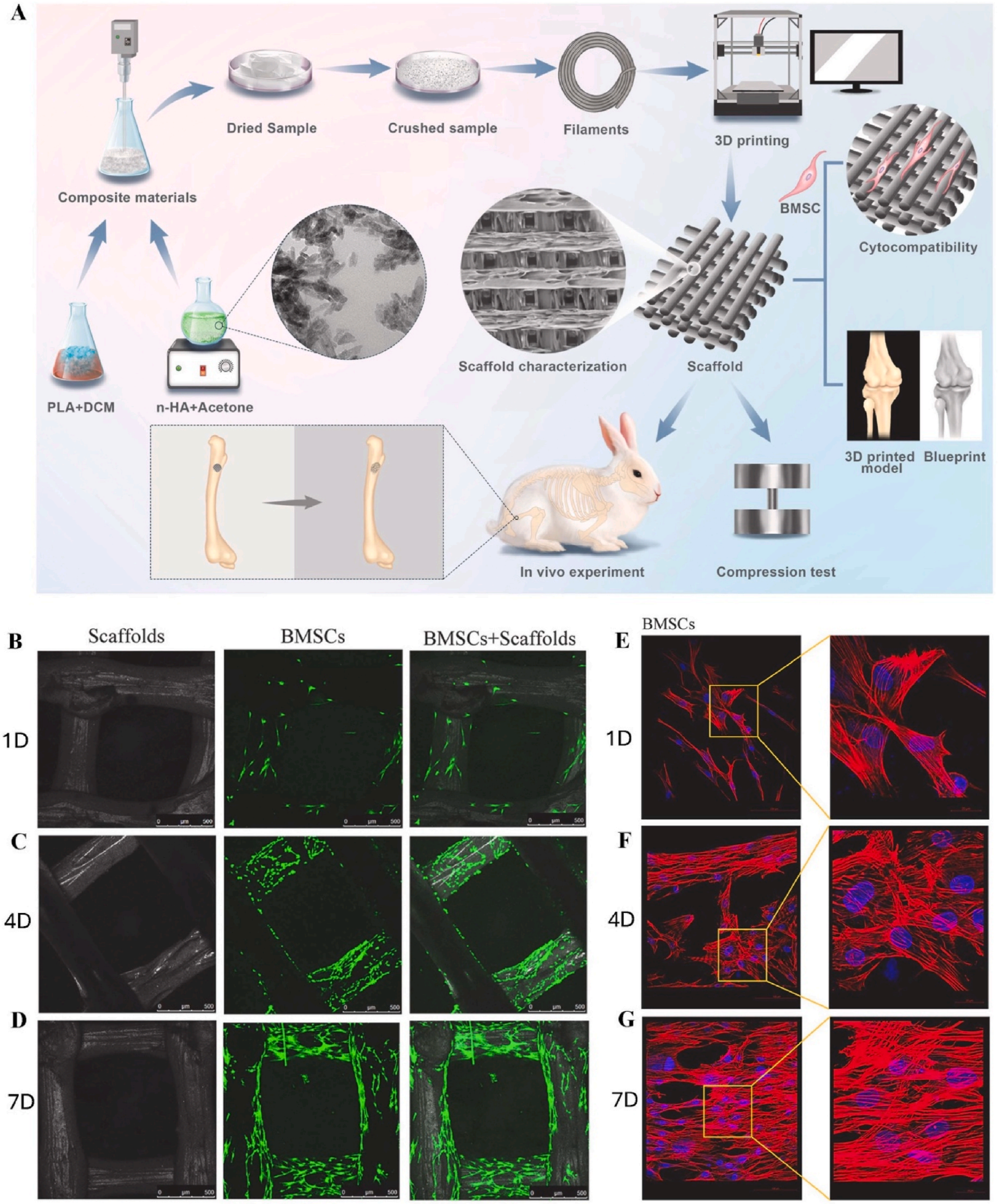

Fig. 7. 3D-Printed PLA Composite Scaffolds for Bone Regeneration. (A) Schematic illustration of the preparation and application of PLA/n-HA scaffolds for osteogenesis reconstruction. The PLA/n-HA composite material was prepared using a wet mixing method, and 3D-printed composite scaffolds were fabricated from PLA/n-HA filaments. (B–G) Biocompatibility of 3D-printed PLA/n-HA scaffolds. (B–D) Live staining of scaffolds loaded with bone marrow stromal cells (BMSCs) after 1, 4, and 7 days of culture. (E–G) Cytoskeleton F-actin staining of cells on the scaffolds at days 1, 4, and 7, illustrating cell attachment and proliferation over time [113].

inflammation. These features make them promising candidates for biodegradable implants, though further optimization is needed to ensure homogeneity and stability over time [155].

PLA-based bioresorbable scaffolds (BRS) are also being explored for coronary stents, addressing thrombogenicity and deployment challenges often faced by thick-strut stents. Functionalized nanofillers, such as LA-Ta_2O_5 and LA-HA, were incorporated to enhance tensile strength, modulus, and nanofiller dispersion, supporting scaffold stability. Finite element analysis revealed that reduced strut thickness maintained radial strength, though further testing on long-term stability and fatigue performance is required [152].

Furthermore, 3D-printed PLA nanocomposites, particularly those with hydroxyapatite (n-HA), demonstrate enhanced osteogenic potential for bone regeneration. For example, PLA/n-HA scaffolds fabricated via fused deposition modeling achieved optimal strength and cell attachment at 30 % n-HA content, while higher concentrations negatively affected mechanical performance (Fig. 7A) [113]. These composites were highly printable, with tunable mechanical strength determined by the n-HA content. The scaffolds exhibited superior biocompatibility and osteogenic induction properties compared to pure PLA scaffolds (Fig. 7B–G). In another study, Liao et al. demonstrated that PLA/acetylated tannin composites, produced using a twin-screw extruder, showed an improved degradation rate in aquatic systems compared to neat PLA, especially in alkaline environments, making them suitable for short-term biomedical applications [156]. The composites were printable with good overall quality, characterized by a distinct brown color. However, printing was constrained to temperatures below 220 °C to prevent defects, particularly at high acetylated tannin loadings.

Overall, while PLA-based nanocomposites offer notable advantages for biomedical applications, challenges such as PLA's brittleness, thermal resistance, and nanofiller dispersion remain. Continued research into surface modifications, fabrication methods, and biocompatible polymer blends is essential to expand PLA's utility across biomedical fields.

4.3. PLA-based nanocomposites for electronics applications

PLA-based nanocomposites hold great promise for addressing environmental challenges associated with traditional non-degradable polymers in electronics. These materials are especially attractive for flexible and wearable devices due to their biocompatibility, biodegradability, and multifunctional properties, including flexibility, mechanical strength, electrical conductivity, and barrier performance. PLA-based nanocomposites have been employed as substrates and dielectric layers in various electronic components, such as transistors and memristors. By incorporating nanofillers, researchers have successfully enhanced PLA's thermal stability, conductivity, and dielectric properties, expanding its potential in electronic applications. Table 4 provides a comprehensive overview of PLA-based nanocomposites developed for electronics application, detailing the types of nanofillers, fabrication techniques, and their impact on dielectric, mechanical, and thermal properties.

To improve the heat resistance and mechanical strength of PLA-based optoelectronic devices, Wang et al. [157] integrated silver nanowires (AgNWs) into a PLA matrix using stereo complex PLA (PLLA:PDLA), forming a highly transparent and conductive film (Fig. 8A). This stereo complex PLA matrix enabled excellent thermal stability up to 200 °C and impressive mechanical flexibility, retaining 96 % conductivity after 10,000 bending cycles. The films also demonstrated rapid biodegradability in alkaline conditions, achieving 91 % degradation within 132 h. When used as electrodes in organic light-emitting diodes (OLEDs), the films displayed high luminous output and flexibility, establishing them as viable options for disposable, environmentally

Table 4
PLA-based nanocomposites for electronics applications.

Nanofiller Type	Synthesis Method	Key Enhancements	Limitations	References
AgNWs	Transfer embedding into PLLA:PDLA stereo complex matrix	↑ Heat resistance, ↑ Flexibility; ↑ Conductivity stability, ↑ OLED performance	Challenges in consistent AgNW alignment affecting stability	[157]
PLA nanowires + Up Conversion Nanoparticles (UCNPs) + W18O49	Nanowire embedding with UCNPs and W18O49	↑ Flexibility, ↑ Light transmission, ↑ Relative sensitivity ↑ Rapid response for temperature sensing	Performance under extreme conditions needs improvement	[158]
MWCNT/Ketjenblack (KB)	3D printing	↑ Piezoresistive response, ↑ Pressure sensitivity	Showed hysteresis and lower stability at higher loadings	[159]
MWCNT + Poly(propylene) glycol (PPG)	Filament extrusion with plasticizer addition	↑ Flexibility, ↑ Electrical conductivity, ↑ Gas sensing response to acetone vapor	Scaling for large-scale textile applications challenging	[160]
TiO_2	Spin coating	↑ Thermal stability; ↑ Morphology and surface modification, ↑ Capacitive and resistive RH sensing	Comparative performance to pristine only	[161]
$MgFe_2O_4$–Ag_2WO_4	Combustion synthesis + coprecipitation; film fabrication	↑ Dielectric property, ↑ Surface charge density, ↑ Energy conversion efficiency	Durability and long-term stability require further study	[162]
CQDs	Electrospinning	↑ High shear piezoelectricity, ↑ Current density, ↑ Stability over 10,000 cycles	Long-term biocompatibility and clinical validation pending	[163]
Gold Nanoparticles (Au)	Electrospinning + electrode modification	↑ Hydrophilic interface; ↑ High selectivity and sensitivity for leukemia cell detectio	Clinical validation pending	[164]
CNTs	Eco-friendly solution casting + 3D printing + electrochemical surface activation	↑ Electrical conductivity, ↑ Tensile strength and modulus, ↑ Sensing capability for redox probes	Surface activation needed for best performance	[165]
4 wt% CNTs	Melt spinning + plasticizer addition	↑ Electrical conductivity, ↑ Humidity sensitivity, ↑ Repeatability and reversibility	Requires optimization of spinning conditions	[166]
Reduced Graphene Oxide (rGO)	Melt compounding + Material Extrusion	↑ Electrical conductivity ↑ Suitable for all-polymer humidity sensor devices	Limited filler loading for optimal performance	[167]
Exfoliated Graphene (GR)	Solution casting (chloroform solvent)	↓ Impedance, ↑ Sensitivity and selectivity for ethanol detection; ↑ Film reusability (≥5 cycles)	Sensitivity depends on ethanol diffusion; limited long-term study	[168]
Carboxyl-functionalized MWCNT (f-MWCNT)	Solution casting + micromolding	↑ Mechanical robustness ↑ Linear electrochemical response to ascorbic acid;	Limited to ex vivo testing; LOD = 180 μM	[169]
MWCNTs + AgNPs	Coating of electrospun PLA nanofibrous scaffolds	↑ Flexible and conductive 3D network, ↑ Repeatable strain-dependent sensitivity, ↑ Accurate human motion detection;	Durability under long-term use needs evaluation	[170]
Carbon Black (CB)	MEX by dual nozzle	↑ Temperature-dependent resistivity change, ↑ Stability over repeated cycles	Limited temperature range (−15 to 50 °C)	[171]

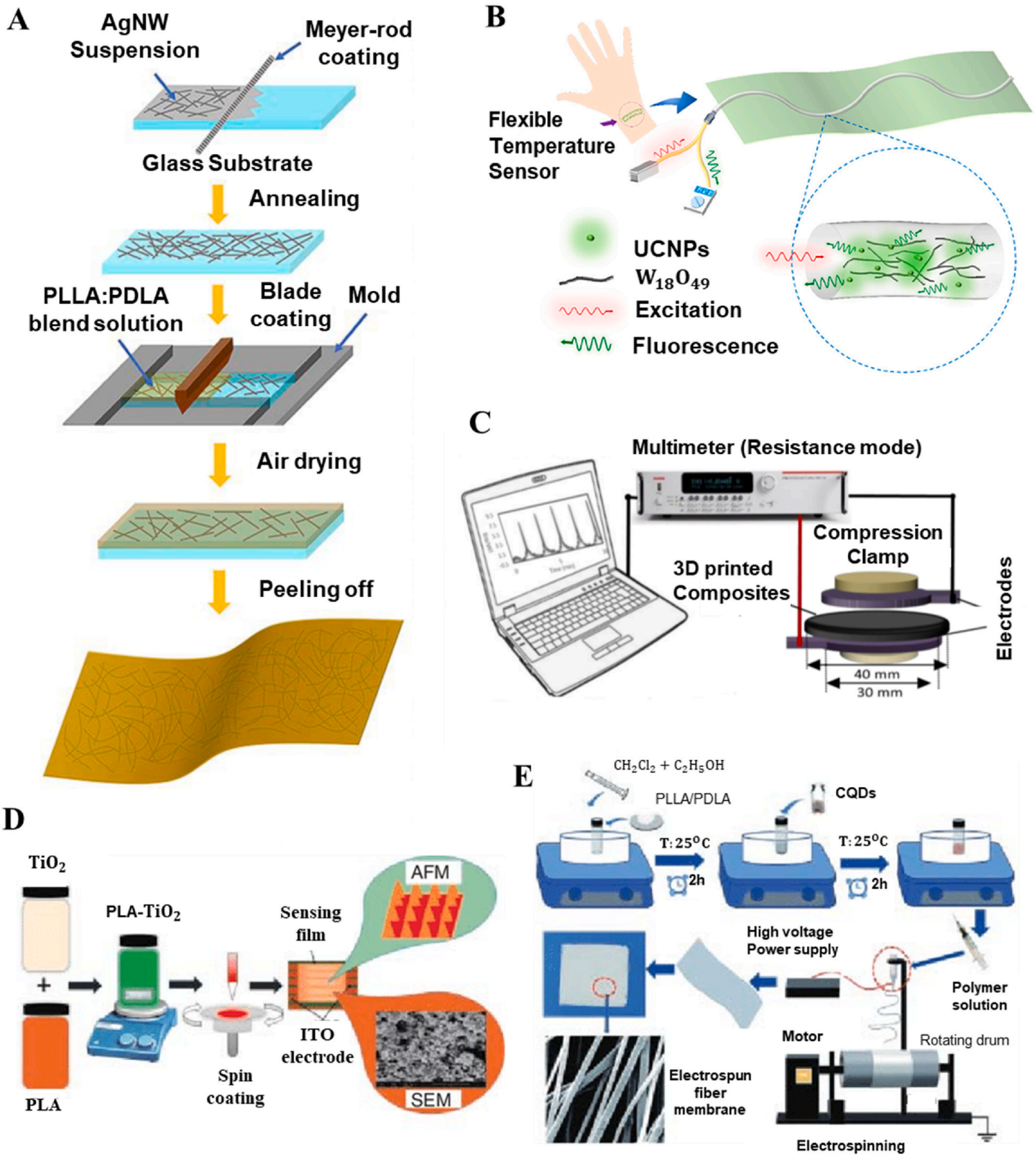

Fig. 8. PLA-Based Nanocomposites for Electronics Applications. (A) Schematic illustration of the fabrication process for Ag NW/PLLA:PDLA composite films, highlighting their conductive properties showing excellent electrical conductivity stability even under the condition of 10,000 repeated bending cycles and 100 tape test cycles [157]. (B) Diagram of a PLA-based temperature sensor, showcasing its design and functionality with rapid temperature response in the range 298–368 K [158]. (C) Experimental setup for testing the piezoresistive response of 3D-printed PLA-based nanocomposites, demonstrating their sensitivity to mechanical stress [159]. (D) Schematic of the spin-coating process used to fabricate PLA-based humidity sensors, illustrating the step-by-step procedure [161]. (E) Schematic diagram of the electrospinning process for creating PDLA/PLLA/CQD nanofiber membranes, emphasizing their potential for advanced electronic applications [163].

friendly electronics. However, challenges remain in consistently aligning AgNWs to ensure stable optoelectronic performance.

In another advancement, Zhang et al. [158] developed a flexible and biocompatible optical temperature sensor using PLA nanowires embedded with up conversion nanoparticles (UCNPs) and W18O49, which enhances the up conversion emission for temperature detection (Fig. 8B). The PLA matrix supports light transmission and flexibility, making it ideal for physiological monitoring. The sensor demonstrated a high relative sensitivity of 1.53 % K^{-1} and rapid response times, making it suitable for real-time health monitoring, though its performance under extreme environmental conditions requires further improvement.

PLA-based nanocomposites are also making strides in pressure sensing. Sanatgar et al. [159] developed piezoresistive materials from PLA/MWCNT and PLA/Ketjenblack (KB) composites using 3D printing. These materials, tested in wearable electronics and soft robotics, showed significant piezoresistive response to compressive stress. With an optimal MWCNT loading of 1 wt%, the composite displayed a gauge factor of 7.6, marking its sensitivity to pressure, though higher loadings in KB-based composites led to increased hysteresis and lower stability (Fig. 8C).

For gas-sensing applications, Silva et al. [160] created PLA/MWCNT filaments with poly(propylene) glycol (PPG), showing potential for detecting volatile organic compounds like acetone. The filaments exhibited reversible resistive responses to acetone vapor and were thermally stable up to 200 °C. The smaller filament diameters provided higher signal response and reversibility, though scaling this design for broader textile applications remains challenging. Amin et al. propose PLA/GO/metal oxide composites for CO_2 sensing, supported by DFT and experimental data. However, the sensor design remains proof-of-concept with limited performance benchmarking (e.g., response time, selectivity), and the practical integration into electronic devices is not fully addressed, reducing its immediate applicability beyond environmental monitoring [172].

PLA has also been explored as a dielectric material in humidity-sensing applications. Mallick et al. [161] developed PLA/TiO_2 nanocomposite films, which exhibited a high response to changes in relative humidity due to increased porosity and surface area. The sensors showed a response time of 40 s and recovery within 20 s, demonstrating cost-effective and stable performance, though the reduction in PLA's melting point may limit thermal applications (Fig. 8D). PLA-based nanocomposites have also been applied in self-powered sensing. A TENG device using PLA/$MgFe_2O_4$/Ag_2WO_4 achieved notable voltage output and motion-triggered sensing; however, challenges such as long-term durability and performance consistency under repeated use remain [162].

In biosensing applications, Wu et al. [164] used PLA nanofibers embedded with gold AuNPs to detect cancer cells, achieving high sensitivity due to AuNPs' conductive properties and enhanced cell adhesion. This setup allowed rapid differentiation between drug-sensitive and drug-resistant leukemia cells, marking a significant advancement in early cancer detection using electrochemical impedance spectroscopy. The versatility of carbon nanomaterials, such as CNTs, graphene, and carbon quantum dots (CQDs), has also been explored in PLA nanocomposites for electronics. Xu et al. [163] developed PLA/CQD nanofibers with high piezoelectric response and luminescence properties, making them suitable for implantable devices and transient electronics. The electrospun nanofibers displayed stable output over 10,000 cycles, emitting multicolor fluorescence under varied laser excitation, thus broadening their application potential (Fig. 8E).

Additionally, Sharifi et al. [165] produced 3D-printable PLA/CNT composite filaments for electrochemical sensing, using a green solvent, Cyrene, to improve electrical conductivity. The CNTs in the composites enhanced electron transfer and the surface activation process further increased conductivity, demonstrating effective ferro/ferricyanide detection and marking the feasibility of sustainable, high-performance sensors. In textiles, Devaux et al. [166] created PLA/CNT multifilament yarns for humidity sensing by melt spinning, optimized for flexibility and crystallinity. Similarly, Gomez et al. [167] developed PLA/reduced graphene oxide (rGO) composites for humidity sensors, showing stable responses to relative humidity cycles, while Chakraborty et al. [168] fabricated PLA/graphene composites for ethanol sensing, achieving stable impedance reduction across multiple cycles due to ethanol diffusion into the conductive network. PLA composites have also been applied in biosensing microneedles. Skaria et al. [169] developed PLA microneedle arrays with carboxylated MWCNTs, achieving a limit of detection for ascorbic acid in porcine skin, showing potential for real-time, minimally invasive health monitoring. For wearable sensors, Gan et al. [170] produced a PLA membrane with MWCNTs and AgNPs, demonstrating repeatable strain sensitivity and antibacterial properties against *E. coli* and *S. aureus*. Although the membrane's conductivity declined slightly after washing, indicating a need for stronger nanoparticle adhesion, this design presents a promising path forward for flexible electronics.

Temperature sensors also benefit from PLA nanocomposites. PLA/Carbon Black (CB) sensors fabricated using dual-nozzle 3D printing exhibited stable resistivity changes in response to temperature fluctuations. In a [0°/90°] layer orientation, the composite demonstrated a temperature coefficient of resistance over 20 times higher than that of standard Pt-based detectors, albeit with slower response times due to PLA's low thermal conductivity [171]. Additionally, PLA nanocomposites have been explored for enhanced dielectric properties. Botlhoko et al. combined PLA with PCL, boehmite alumina (BA), and reduced graphene oxide (TERGO) to improve dielectric constant, tensile modulus, and strength, demonstrating suitability for flexible electronic components [173]. Recent studies further support this potential: a 3D-printed PLA/CNT-based thermal sensor showed both thermoresistive and thermoelectric behavior, though with relatively long response and recovery times, limiting its responsiveness in dynamic environments [174].

Despite these advancements, PLA-based nanocomposites in electronics face challenges, particularly in thermal resistance, limiting their applicability in high-temperature processing techniques like sputtering. PLA's low conductivity also restricts functionality, though increasing NP loading improves conductivity at the expense of flexibility due to potential nanomaterial agglomeration. Stability under high humidity or temperature is also a concern, as PLA's biodegradability may compromise longevity in some environments. Continued research is necessary to balance conductivity, mechanical strength, and flexibility, driving PLA-based nanocomposites toward broader adoption in sustainable electronics.

4.4. PLA-based nanocomposites for other applications

PLA-based nanocomposites have found applications beyond those discussed in electronics, packaging, and biomedical fields. Their versatility and environmental benefits have made them attractive in areas such as fire retardancy, self-cleaning devices, pollutant removal, air filtration, heavy metal separation, and agricultural nano pesticides. One example is in foam structures, where PLA/CNC nanocomposites developed by Borkotoky et al. [175] showed significant enhancements in foam cell density and size due to the addition of CNCs, leading to improved mechanical properties. Such advancements highlight PLA's potential in lightweight and structurally robust materials.

Lignin, a natural biobased char-forming agent, has shown promise as a fire retardant when incorporated into PLA. Chollet et al. [176] investigated lignin nanoparticles (LNPs) modified with diethyl chlorophosphate (diEtP) and diethyl (2-(triethoxysilyl)ethyl) phosphonate (SiP) as flame-retardant additives. They found that the phosphorylated LNPs, particularly those modified with SiP, provided enhanced thermal stability and delayed ignition, achieving an 18 % reduction in peak heat release rate (pHRR) with only 5 wt% loading, marking an effective eco-friendly solution for flame-retardant applications.

PLA-based nanocomposites have also shown promising potential in environmental remediation, particularly in self-cleaning and pollutant removal via photocatalytic degradation. For example, Sevastaki et al. [177] engineered ZnO nanostructures onto 3D-printed PLA scaffolds, achieving the photocatalytic degradation of 95 % of paracetamol in aqueous solution under UV-A irradiation within 30 min. This study highlights the viability of PLA-based composites as functional platforms for the degradation of pharmaceutical contaminants in wastewater treatment applications. Similarly, Bobirică et al. [178] developed PLA/TiO_2 hybrid nanofibers on fiberglass membranes to degrade ampicillin in water, achieving up to 95.2 % degradation within 30 min under UV irradiation. However, the low stability of PLA under UV and acidic conditions led to partial degradation, releasing TiO_2 nanoparticles and affecting the membrane's structural integrity and efficiency over time.

In air filtration, the hybrid PLA/TiO_2 fibrous membrane developed by Wang et al. [179] showcased high efficiency. The membrane, with a nanoporous structure, achieved a filtration efficiency of 99.996 % while maintaining low-pressure drops, making it suitable for high-efficiency air filters. Additionally, it displayed antibacterial activity, achieving a 99.5 % reduction in *Staphylococcus aureus*, further underscoring its utility in air purification and antibacterial surface applications.

Heavy metal ion separation is another innovative use of PLA-based nanocomposites. Kian et al. [180] developed dual-layer membranes made from PLA and PBS reinforced with cellulose nano whiskers (CNWs) for filtering cobalt (Co^{2+}) and nickel (Ni^{2+}) ions. With 3 % CNW loading, these membranes exhibited enhanced mechanical strength, water flux performance, and porosity while achieving removal rates of 83 % for Co^{2+} and 84 % for Ni^{2+} ions, illustrating the potential of PLA nanocomposites in water purification.

In agriculture, PLA-based nanocomposites have shown potential as environmentally friendly nano pesticides. Yu et al. [181] explored tannic acid (TA)-based formulations to improve foliar adhesion and retention in pesticide applications, developing Abam-PLA-Tannin-NS and Azox-PLA-Tannin-NS nano pesticides to avoid groundwater contamination. Tannic acid improved adhesion and retention on foliage by chemically modifying abamectin and azoxystrobin. These formulations provided enhanced foliar retention, sustained release profiles, improved photostability, and strong antifungal efficacy, demonstrating PLA's potential for safer, more efficient agrochemical delivery.

These studies underscore the versatility of PLA-based nanocomposites and their suitability for a wide range of applications. However, challenges remain, such as improving the stability and durability of PLA under various environmental conditions and ensuring sustainable, scalable production methods. Future research focused on overcoming these challenges will help to realize the broader potential of PLA nanocomposites in diverse industries.

5. Challenges and opportunities for PLA-based nanocomposites

Despite remarkable progress in the development of PLA-based nanocomposites, several critical challenges must be addressed to realize their full commercial and functional potential. These challenges span the domains of materials engineering, processing, environmental sustainability, and economic viability.

Nanofiller Dispersion and Interfacial Compatibility: Uniform dispersion of nanofillers within the PLA matrix remains a key bottleneck due to the high surface energy and tendency of nanomaterials to agglomerate [182]. Poor dispersion leads to inhomogeneous properties and diminished reinforcement effects. Surface functionalization (e.g., silanes, surfactants, polymer grafting) and in situ polymerization have shown promise in enhancing nanofiller–matrix interactions [183,184]. Mechanical techniques such as ultrasonication and high-shear mixing can break up agglomerates, while compatibilizers like maleic anhydride-grafted PLA improve stress transfer at the filler–matrix interface [23]. Optimizing solvent polarity or using twin-screw extrusion further aids in achieving uniform distribution [185].

Environmental and Long-Term Stability: PLA's biodegradability is advantageous but also presents durability challenges under conditions involving humidity, temperature, and enzymatic exposure. Some nanofillers, such as layered silicates or nano-hydroxyapatite, improve thermal aging and oxidative stability, while others may accelerate hydrolytic degradation if poorly dispersed or chemically reactive [186–188]. Achieving an optimal balance between degradation rate and application lifespan remains an ongoing area of research.

Scalability and Processing Trade-Offs: Large-scale production of PLA nanocomposites is constrained by energy-intensive processes and solvent-based techniques that may be unsustainable. Solution casting offers excellent control over nanofiller dispersion but requires solvent recovery systems, limiting its scalability. In contrast, melt blending and extrusion are more scalable but involve high shear and thermal loads that can affect filler integrity [189]. Life cycle assessment (LCA) studies have shown that the overall environmental footprint of PLA nanocomposites depends heavily on filler type, fabrication method, and end-of-life treatment [54,190,191].

Economic Feasibility: The cost of high-performance nanofillers and the complexity of their synthesis or functionalization remain barriers to widespread adoption. Nonetheless, emerging solutions—including bio-derived nanofillers, green solvent systems, and process intensification strategies—offer pathways to reduce both economic and environmental costs. Additionally, leveraging second-generation feedstocks and biorefinery integration can improve material circularity and lower raw material expenses.

Opportunity Outlook: To fully unlock the potential of PLA nanocomposites, future research may focus on: (i) advanced interfacial engineering strategies, (ii) scalable, solvent-free fabrication methods, and (iii) system-level assessments of sustainability and performance. Multidisciplinary collaboration among material scientists, process engineers, and policy stakeholders will be essential to accelerate industrial translation.

6. Conclusion

PLA-based nanocomposites represent a promising class of sustainable materials with the potential to replace conventional petrochemical polymers in a wide range of applications. Leveraging PLA's biodegradability, mechanical integrity, and biocompatibility—while addressing its inherent limitations—researchers have demonstrated significant improvements in performance through nanofiller incorporation.

This review has highlighted how different nanofillers—ranging from carbon-based materials (e.g., CNTs, graphene) to metal oxides (e.g., ZnO, AgNPs) and biobased reinforcements (e.g., nanocellulose, chitin)—enhance specific functionalities, including mechanical strength, barrier performance, UV resistance, electrical conductivity, and bioactivity. Hybrid nanofiller systems further extend the multifunctional capacity of PLA composites, enabling application-specific material design. Common fabrication methods such as melt blending, in situ polymerization, electrospinning, and material extrusion (MEX) 3D printing offer diverse pathways for scalable and targeted composite formation.

From a commercial perspective, PLA-based nanocomposites are increasingly attractive for sectors prioritizing sustainability, including food packaging, biomedical devices, and wearable electronics. In packaging, they provide biodegradable, recyclable solutions aligned with circular economy principles. In the biomedical field, their safe degradation profile enables use in implants, tissue scaffolds, and drug delivery systems. In electronics, their potential for low-cost, flexible, and disposable devices is being explored, although thermal resistance and conductivity remain areas for improvement.

Looking ahead, realizing the full potential of PLA nanocomposites will depend on continued innovation in dispersion control, degradation tuning, and green processing. Equally important will be comprehensive life-cycle assessments and techno-economic evaluations to ensure that environmental benefits align with market demands. As global sustainability goals intensify, PLA nanocomposites are well-positioned to contribute to the next generation of environmentally responsible materials and manufacturing.

CRediT authorship contribution statement

Md Shariful Islam: Investigation, Visualization, Writing – original draft. **G.M. Fazley Elahee:** Investigation, Writing – review & editing. **Yuhui Fang:** Investigation, Writing – review & editing. **Xiong (Bill) Yu:** Writing – review & editing. **Rigoberto Castillo Advincula:** Writing – review & editing. **Changyong (Chase) Cao:** Conceptualization, Supervision, Resources, Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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