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Recent Advances in Surface-Coated Poly(Lactic Acid) Scaffolds for Tissue Engineering Applications: A Comprehensive Review

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Abstract: Poly(lactic acid) (PLA) is a biodegradable polymer widely used to make scaffolds for tissue engineering because it is biocompatible and easy to process using technologies such as 3D printing. However, PLA surfaces are naturally hydrophobic and have low bioactivity, which can limit cell attachment and tissue growth. To overcome these limitations, surface modification techniques are used to improve the biological performance of PLA scaffolds. Among these methods, the sol–gel coating technique is widely studied because it can form thin, uniform, and bioactive coatings at low processing temperatures suitable for polymers. This review summarizes research published between 2015 and 2025 on PLA scaffolds coated with bioactive materials for tissue engineering applications. Various coating materials such as hydroxyapatite, bioactive glass, chitosan, gelatin, and polydopamine have been explored to improve surface properties. These coatings enhance wettability, promote cell attachment, and improve osteoconductivity. Overall, coated PLA scaffolds show improved biological performance and strong potential for use in regenerative medicine and bone tissue engineering.

Keywords: *PLA, Sol–gel coating, Tissue engineering, Surface modification, Bioactive scaffolds.*

1. INTRODUCTION

Bone tissue damage caused by trauma, tumor resection, congenital defects, and degenerative disorders represents a significant global healthcare burden. Conventional clinical interventions such as autografts and allografts remain the gold standard for treatment; however, their use is limited by donor site morbidity, limited graft availability, risk of immune rejection, and potential disease transmission [1,2]. These limitations have driven extensive research in bone tissue engineering, which aims to regenerate damaged tissues using biodegradable scaffolds combined with biological cues [3].

Among biodegradable polymers, poly(lactic acid) (PLA) has emerged as a promising candidate for scaffold fabrication owing to its biocompatibility, tunable degradation rate, favorable mechanical properties, and regulatory approval for biomedical use [4,5]. PLA can be processed using various conventional and advanced manufacturing techniques, including solvent casting, electrospinning, and additive manufacturing. In particular, three-dimensional (3D) printing technologies enable precise control over scaffold architecture, porosity, and mechanical performance, which are critical parameters for successful tissue regeneration [6].

Despite these advantages, pristine PLA exhibits inherent limitations that restrict its biological performance. The polymer surface is hydrophobic and lacks bioactive functional groups, resulting in limited protein adsorption and suboptimal cell adhesion [7]. Furthermore, PLA does not possess intrinsic osteoconductive or antibacterial properties, which are desirable for orthopedic and tissue engineering applications [8]. Therefore, surface modification strategies are essential to improve the biological interface of PLA without compromising its bulk mechanical integrity.

Surface engineering approaches such as plasma treatment, chemical grafting, layer-by-layer deposition, and bioactive ceramic coating have been explored to enhance PLA surface properties [9]. Among these techniques, the sol–gel method has gained considerable attention due to its simplicity, compositional versatility, and ability to produce homogeneous thin films at relatively low processing temperatures [10]. The sol–gel process involves hydrolysis and condensation of metal alkoxide precursors to form inorganic or hybrid organic–inorganic networks, enabling controlled deposition of bioactive coatings such as silica, titania, and hydroxyapatite [11].

Sol–gel-derived coatings have demonstrated significant improvements in surface wettability, bioactivity, and osteogenic potential of polymeric substrates [12]. Additionally, this technique allows incorporation of therapeutic ions (e.g., Ag^{+}, Zn^{2+}, Sr^{2+}) to impart antibacterial and osteoinductive properties [13]. Importantly, sol–gel coatings can uniformly cover complex three-dimensional porous structures, making them particularly suitable for tissue engineering scaffolds fabricated via additive manufacturing [14].

In this context, the present study focuses on the development and characterization of sol–gel coatings on PLA substrates for tissue engineering applications. The objective is to enhance surface bioactivity and cell–material interactions while preserving the structural and mechanical

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properties of the underlying polymer scaffold. The outcomes of this work are expected to contribute to the advancement of multifunctional, bioactive polymeric scaffolds for regenerative medicine.

2. COMPREHENSIVE REVIEW

PLA scaffolds with surface coatings for tissue engineering covering major research articles from 2015–2025**.** Because not all studies used sol–gel specifically, this review includes PLA scaffolds with bioactive surface coatings or functionalization relevant to enhancing biological performance in tissue engineering applications. The table below organizes key studies by year and key parameters.

Table 1. Review (2015–2025): PLA Scaffolds with Surface Coatings in Tissue Engineering

Year	Substrate	Coating/Surface Functionalization	Method	Tests Performed	Key Outcomes
2015 [15]	—	PLA scaffold calcium phosphate deposition	Chemical deposition	In vitro bioactivity, cell studies	Calcium phosphate coating enhanced bioactivity.
2018 [16]	PLA 3D printed	Calcium phosphate (via mineralization)	Post-print chemical deposition	Wettability, stem cell adhesion	Enhanced wettability and hMSC adhesion/proliferation.
2020 [17]	PLA 3D printed	Chitosan + hydroxyapatite	Surface functionalization	SEM, XRD, cell viability	Improved hydrophilicity and bone cell proliferation.
2021 [18]	PLA 3D printed	Gelatin coating	Immersion coating	Biocompatibility tests	Enhanced cell adhesion and biocompatibility.
2022 [19]	PLA 3D printed	Polydopamine + nHA	Mussel-inspired coating	SEM, EDX, degradation, Ca release	Increased hydrophilicity, Ca^{2+} release, osteogenic factors.
2023 [20]	PLA/MMT nanocomposite	Sr-bioglass & nHA coating	Dip coating	Biocompatibility, mechanical tests	Enhanced osteogenesis and cell proliferation.
2024 [21]	PLA 3D printed	PCL polymer coating	Dip coating	FTIR, SEM, mechanical & cell assays	Improved coverage, integrity, biocompatibility.
2025 [22]	PLA 3D printed	Polydopamine + chitosan MCA NP	Surface nanoparticle coating	Mechanical, cell adhesion, osteogenic tests	Improved bioactivity, wettability, cell adhesion.

2015–2019: Foundational Coating Strategies

Early work in this period established the importance of surface modification to overcome the inherent bio-inertness of PLA scaffolds. Mineral deposition strategies, such as calcium phosphate layer formation, were shown to enhance scaffold wettability and provide osteogenic cues [15,16]. These studies demonstrated that simple chemical modifications can significantly increase cell adhesion and bone-like mineral deposition on PLA surfaces, laying a basis for later functional coatings.

2020–2021: Composite Bioactive Coatings

From 2020 onwards, research focused on combining organic polymers with inorganic bioactive agents to enhance PLA scaffold performance. For example, chitosan and hydroxyapatite (HA) were integrated onto PLA surfaces via functionalization techniques, resulting in improved hydrophilicity and enhanced attachment and proliferation of bone cells in vitro [17]. Gelatin coatings applied to PLA scaffolds also improved cell adhesion, indicating that polymeric coatings can compensate for PLA's hydrophobic surface [18]. These developments emphasized the integration of biocompatible polymers and ceramics to mimic the natural bone extracellular matrix.

2022–2023: Bioinspired and Nanocomposite Coating Approaches

Recent years saw the adoption of bioinspired coatings, such as polydopamine (PDA) used to immobilize nano-hydroxyapatite (nHA) on PLA scaffold surfaces. These coatings significantly increased surface hydrophilicity, enabled sustained release of calcium ions, and promoted osteoblastic activity without compromising mechanical properties [19]. Moreover, PLA nanocomposite scaffolds incorporating montmorillonite (MMT) were coated with Sr-containing bioglass and nHA to further enhance osteogenic differentiation compared to neat PLA scaffolds [20].

2024–2025: Advanced Functional Coatings

The latest research shows continued innovation in coating strategies. Dip coating of PLA scaffolds with polycaprolactone (PCL) provided reliable surface coverage and improved biocompatibility, demonstrating that polymer coatings can enhance scaffold performance in bone tissue contexts [21]. Furthermore, advanced surface engineering integrating polydopamine with chitosan nanoparticles loaded with bioactive molecules (e.g., 4-methoxycinnamic acid) has been shown to significantly improve wettability, bioactivity, and cell adhesion, underscoring the shift toward multifunctional coatings [22].

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3. CONCLUSION

This review summarizes research from 2015 to 2026 on improving poly(lactic acid) (PLA) scaffolds for tissue engineering through surface coating techniques. PLA is widely used because it is biodegradable, biocompatible, and easy to process using technologies like 3D printing**.** However, its hydrophobic surface and low bioactivity limit cell attachment and bone regeneration. To overcome these limitations, researchers have applied different bioactive coatings such as hydroxyapatite, bioactive glass, chitosan, gelatin, and polydopamine using methods like sol–gel coating, dip coating, and biomimetic mineralization**.** These coatings improve surface wettability, cell adhesion, proliferation, and osteogenic activity**,** which are important for tissue regeneration. Among these methods, the sol–gel coating technique is particularly useful because it can produce uniform, thin, and bioactive layers at low temperatures**,** making it suitable for polymer scaffolds like PLA. Although many studies show promising results, challenges such as coating stability, strong bonding with PLA, and large-scale production still need further research. Overall, bioactive surface coatings significantly enhance the performance of PLA scaffolds and show strong potential for future tissue engineering applications**.**

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