Current Trends in Biomedical Engineering & Biosciences
ISSN: 2572-1151

Juniper Publishers
key to the Researchers

Review Article
Volume 23 Issue 5 - October 2025
DOI: 10.19080/CTBEB.2025.23.556122

Curr Trends Biomedical Eng & Biosci

Synthetic Elastomeric Scaffolds Based on Poly (Glycerol-Succinic Acid) for Tissue Engineering: A Review

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Submission: October 13, 2025; **Published:** October 22, 2025

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Abstract

Tissue engineering has emerged as a pivotal field in regenerative medicine, where biomaterials serve as the foundational scaffolds for cell proliferation and tissue formation. Recent research has increasingly focused on synthesizing biodegradable biopolymers via polycondensation of dialcohols and diacids. Among these, novel green highly branched polyesters (HBPEs) have garnered significant attention due to their unique architectural features, including numerous end groups, low viscosity, high solubility, and straightforward synthesis. A prime example is poly (glycerol succinate) (PGSu), a polyester derived from glycerol and succinic acid.

PGSu shares key characteristics with the well-established biomaterial poly (glycerol sebacate) (PGS), which has been extensively explored as a scaffold or additive for engineering various tissues, such as cardiac, bone, neural, and ocular. This review comprehensively summarizes the recent progress and advancements in the development and application of biodegradable elastomers based on poly (glycerol-succinic acid) for tissue engineering.

Keywords: Succinic acid; Elastomeric biomaterials; Poly(glycerol-succinate); Glycerol sebacate; Biopolymers

Abbreviations: PGS: Glycerol Sebacate; PGSu: Poly Glycerol Succinate; HBPEs: Highly Branched Polyesters; PLA: Polylactic Acid; PGA: polyglycolic acid; PCL: Poly E-Caprolactone; PLGA" Polylactic-Co-Glycolic Acid; PGS: Poly (Glycerol Sebacate; Pus: Polyurethanes; TMC: Trimethylene Carbonate

Introduction

Tissue engineering is poised to be a cornerstone of future therapeutic strategies for restoring damaged tissues [1-3]. A central challenge in this field is the development of advanced biomaterials that can effectively support this restoration process. The evaluation of the mechanical, biological, and physical properties of newly developed biomaterials is therefore essential, making the introduction of novel, functional biomaterials a primary research focus [1-3]. In regenerative medicine, biomaterials provide the foundational scaffolds that guide cell division and tissue expansion [4,5]. The critical properties of these materials-such as biocompatibility, biodegradability, and hydrophilicity-must be carefully optimized. Key considerations include their water absorption capacity and their rate of degradation over time, which are vital for designing effective scaffold systems [4,5].

Biodegradable polymers, defined as materials that can be broken down by environmental microbes or in vivo biological fluids, have been widely used to create tissue engineering scaffolds. This category includes polylactic acid (PLA), polyglycolic acid (PGA), poly(ε-caprolactone) (PCL), and polylactic-co-glycolic acid (PLGA), all of which undergo hydrolysis in vivo. However, these materials often lack the flexibility of native living tissues and frequently require toxic solvents for processing [5,6]. In contrast, elastomeric materials offer high biocompatibility, strength, design adaptability, mechanical compliance, and cost-effectiveness, leading to their use in diverse therapeutic products [7]. Numerous implantable devices, including catheters, drug delivery systems, and prosthetic and cardiac devices, have been fabricated from conventional and engineered rubbers such as silicones, polyurethanes, polyolefins, and polydienes [7].

Recent research has concentrated on Poly (glycerol sebacate) (PGS), a crucial biocompatible polymer that addresses many of these requirements [7,8]. This "biorubber," synthesized by the polycondensation of glycerol and sebacic acid, possesses suitable mechanical and physical characteristics. PGS demonstrates excellent mechanical properties, remarkable flexibility, and tunable biodegradability, making it beneficial for neuron regeneration, vascular repair, and cardiac tissue engineering [7,8]. The mechanical properties and degradation rates of PGS can be tailored for diverse applications by altering reactant concentrations and curing conditions. Nonetheless, its intrinsic hydrophobicity limits its utility in emerging applications like 3D cell encapsulation [9].

This limitation has spurred interest in Highly Branched Polyesters (HBPEs), which are noted for their unique structures, high functionality, low viscosity, good solubility, and synthetic simplicity. The favorable plasticizing properties of HBPEs are largely attributed to atomic-scale free-volume holes within their structure. The synthesis of novel bio-based HBPEs-such as poly (glycerol succinate) (PGSu), poly (glycerol succinate-co-maleate), and poly (glycerol adipate)-has expanded the toolkit for various applications [9-14]. PGSu shares significant similarities with the well-established PGS and has been proposed as a scaffold material or additive for engineering cardiac, bone, cartilage, nerve, and ocular tissues [9-14]. This article aims to discuss the latest advancements in the application of biodegradable elastomers based on poly (glycerol-succinic acid) (PGSu) in the field of tissue engineering.

Elastomeric Biomaterials

The use of elastomers in medical devices dates to the mid-1890s, coinciding with the emergence of the rubber industry. Even prior to the discovery of the vulcanization process, vulcanized natural rubber was already being utilized in items such as surgical gloves. Owing to their mechanical compliance, strength, design versatility, biocompatibility, and cost-effectiveness, elastomeric materials have since been incorporated into a wide range of therapeutic products. Various conventional and engineered rubbers—including silicones, polyurethanes, polyolefins, and polydienes-have been employed in numerous implantable devices, such as cardiac and prosthetic implants, catheters, transdermal drug delivery systems, orthodontics, and ophthalmological materials [15-18].

By the late 1990s, degradable elastomeric biomaterials were being developed specifically for tissue engineering and are now used in FDA Class III medical devices. This review focuses on elastomeric biomaterials, including synthetic, degradable, inert, and natural bioelastomers, particularly in the context of tissue-building applications. For each elastomeric polymer discussed, synthesis, biocompatibility, and degradability are examined, along with examples of surgical and biomedical uses [15]. This is generally followed by a detailed analysis of the polymer's mechanical properties. The objective is to identify the most promising elastomers and address unique challenges associated with their production and use as biomaterial frameworks in sensitive tissue engineering scenarios [15,16].

Polyurethanes (PUs) represent a broad family of polymeric materials recognized for their direct blood compatibility and mechanical adaptability. They exhibit a wide range of chemical compositions, mechanical properties, tissue-specific biocompatibility, and tunable biodegradability [19]. These versatile macromolecules are used not only in non-medical applications-such as protective fabrics, adhesives, coatings, and air filters-but also extensively in pharmaceuticals and biomedicine. Their high biocompatibility, low surface tension, high oxygen permeability, and resistance to trypsin make PUs mechanically like native tissues. Consequently, they are used in scaffolds for soft and hard tissue engineering, antimicrobial filters, sensors, wound dressings, drug carriers, and for cellular protein incorporation [20,21,22].

PUs was first synthesized in the 1930s by Bayer and colleagues. These synthetic polymers are produced via one- or two-step polymerization processes, involving three essential components: (i) a polyol (e.g., polyether, polycarbonate, polyester polyol, or polycaprolactone), (ii) a diisocyanate, and (iii) a crosslinker. The reaction between diisocyanate and polyol forms the urethane linkage (–NHCOO–), the fundamental structural unit of PUs. The choice of polyol-with nearly 500 commercial varieties available—significantly influences the physicochemical properties of the resulting PU; high molecular weight polyols yield flexible PUs, while lower molecular weight polyols produce more rigid structures [23,24].

For instance, a biodegradable polyurethane based on a soft segment of poly(δ-valerolactone-co-ε-caprolactone) (PVCL, molecular weight = 6000) and a hard segment of 1,4-diisocyanatobutane (BDI) with putrescine as a chain extender exhibited an initial modulus of 2.8±1.3 MPa in the dry state. This is notably lower than the 12.1±2.5 MPa initial modulus of a polyurethane derived from semi-crystalline polycaprolactone (PCL), BDI, and putrescine. However, both values remain higher than those of natural soft tissues. Incorporating hydrophilic poly (ethylene glycol) (PEG) into the soft segment presents a viable strategy to further reduce the initial modulus in a physiological environment. PEG enhances the polymer's water absorption capacity; absorbed water in a "bound state" can form hydrogen bonds with polymer chains and act as a plasticizer, thereby lowering the initial modulus [25-28].

The development of biodegradable elastomers has been driven by limitations of earlier biodegradable thermoplastics, such as bulk degradation, stiff mechanical properties, and the release of acidic degradation products [25,26]. Recently, interest has

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grown in soft, chemically cross-linked biodegradable elastomers. The Langer group at MIT introduced a family of crosslinked elastomers known as PPS, which are both cost-effective and biocompatible. The synthesis of these polymers is exemplified by poly (glycerol sebacate) (PGS), a prominent member of the PPS family listed in Table 1, which shows promise for nerve and vascular tissue engineering [6,27]. Studies have shown that PGS degrades primarily via surface erosion, preserving its structural integrity and shape in vivo.

This makes PGS-based biomaterials highly suitable for soft tissue applications requiring specific micro-features, such as gecko-inspired surgical adhesives, microfabricated scaffolds, cardiovascular tissue engineering, and small-diameter nerve grafts. However, the current utility of PGS elastomers is limited to relatively short-term soft tissue applications due to their narrow range of mechanical properties and degradation rates. Recently, a versatile polymer platform based on endogenous mammalian metabolites-using xylitol as a primary monomer-has been reported, enabling the production of hydrogels and elastomers with tunable mechanical properties and in vivo degradation rates [27,28,6]. Over the past two decades, research into soft, biodegradable elastomers for diverse applications has expanded significantly.

These materials are indispensable in soft tissue engineering. This study has focused on the synthesis, material properties, and scaffold fabrication techniques of such elastomers. While they are generally biocompatible and mechanically compliant, several challenges remain concerning their degradation and synthesis. First, the acidic degradation products of very soft degradable elastomers can cause cytotoxicity, hindering their use as cell delivery vehicles. Second, there in vivo degradation rates are often too rapid for practical soft tissue engineering. Third, synthesis methods (e.g., for PPS) require refinement to meet stringent quality control standards in tissue engineering. Therefore, further research is needed before these soft degradable elastomers can be widely applied in clinical settings, particularly in: (i) developing novel synthetic approaches to enhance manufacturing capacity and reproducibility, and (ii) creating new hybrid elastomeric biomaterials with slower degradation rates to meet the clinical requirements of specific tissues [1,27] (Table 1).

Table 1: Comparison of Key Biodegradable Elastomer Classes for Tissue Engineering.

Category	Examples	Key Characteristics	Advantages	Limitations / Associated Challenges	Ref
Polyurethanes (PUs)	PUs based on PCL, PVCL, PEG	Direct blood compatibility, mechanically adaptable, tunable biodegradability.	High biocompatibility, mechanically similar to native tissues, wide range of applications .	Can be stiffer than natural soft tissues; some formulations require toxic solvents.	[5,6,19,20,21]
Cross-linked Polyesters (PPS)	Poly (glycerol sebacate) (PGS)	Degrades primarily by surface erosion; soft and flexible	Excellent biocompatibility, cost-effective, maintains structural integrity during degradation	Narrow range of mechanical properties, relatively fast degradation, inherently hydrophobic	[6,9,27]
Highly Branched Polyesters (HBPEs)	Poly (glycerol succinate) (PGSu)	Unique structure, numerous end groups, low viscosity, high solubility	Simple synthesis, green bio-based precursors, excellent plasticizing properties	Requires further research to optimize mechanical properties and degradation rates for specific applications.	[9,14]
Hybrid Elastomers	Xylitol-based polymers	Based on endogenous metabolites; highly tunable mechanical properties and degradation rates	High biocompatibility potential, can produce both hydrogels and elastomers	In early stages of development; requires extensive in vivo validation for clinical potential.	[6,27,28]

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Table 2: Summary of Studies on Poly (Glycerol-Succinic Acid)-Based Elastomeric Composites.

Material System / Composite	Key Findings	Potential Application	Ref
PGSu as an additive for PLLA & PLCL fibers	• Improved polymer chain mobility	Biocompatible fibers for medical applications	[36]
	• Enhanced crystallinity of bicomponent fibers		
	• Maintained biocompatibility with L929 cells		
PGSuc coating for Mesoporous Bioactive Nanoparticles (MSNs)	Improved physicochemical properties of scaffolds	Hybrid scaffolds for bone tissue engineering	[47]
	• Enhanced ALP activity & mineralization (Alizarin Red)		
	• Promoted osteogenic differentiation of stem cells		
PGSeSu (PGS modified with Succinic Acid)	• Increased carbonyl groups & water absorption	Biodegradable elastomers with tunable degradation rates	[48]
	• Enhanced degradability		
PLA / PGSMA (Poly (glycerol succinate-co-maleate)) blends	• 53% improvement in elongation at break	Toughened, sustainable polymer blends for engineering	[49]
	• 175% improvement in notched Izod impact strength		
	• Toughness via particle debonding & shear yielding		
PGSMA / PLA / PBS thermoplastic blends	• Tensile strength: 33.8 MPa	High-performance bio-based thermoplastic composites	[50]
	• Tensile modulus: 1.47 GPa		
	• Notched Izod impact: 159 J/m (similar to polypropylene)		
PCL-PPSu copolymer with silver particles	• Low processing temperature	3D-printed scaffolds for skin regeneration therapies	[51]
	• Adaptability to 3D printing		
	• Antimicrobial properties		
PCL / PGSu / n-HA nanocomposites with PPy coating	• Tunable Young's modulus (4.5 - 11.5 MPa)	Multifunctional scaffolds for neural and other tissue engineering	[52]
	• Electrical conductivity (~$5x10^{-2}$ S/cm)		
	• Antibacterial activity & enhanced cell viability		
Copolymers from SA, Glycerol, Sebacic Acid, ε-Caprolactone with n-HA & C30B	• Reduced glass transition temperature (Tg)	Advanced bio-nanocomposites with tailored properties	[48]
	• Modified tensile strength & Young's modulus		
	• Synergistic effect of nanoparticles on degradation rate		

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Succinic Acid and their Applications

Succinic acid (SA), or butanedioic acid, is a four-carbon dicarboxylic acid that is solid at room temperature (melting point = 187 °C, boiling point = 235 °C) and soluble in water, ether, acetone, and alcohol [29-31]. Classified as "Generally Recognized as Safe" (GRAS), it is used as a flavor enhancer, a pH regulator in food products, and a toothpaste ingredient [29-31]. Biologically, succinate-the dianionic form of succinic acid—functions as a key metabolic intermediate in the mitochondrial tricarboxylic acid cycle within highly active aerobic cells [29-31]. In recent decades, extensive research has focused on developing sustainable alternatives to conventional chemicals from renewable resources [30]. Among promising bio-based platform molecules, glycerol and succinic acid have emerged as particularly valuable for various applications, especially in surfactant production [30]. These developments in polymer chemistry have enabled numerous technological and therapeutic advances over the past fifty years [31-34].

Polymers constitute essential components of medical devices in biotechnology and rehabilitation, ranging from basic catheters to functional prostheses [35]. While linear polymers remain the most widely used macromolecules, alternative architectures-including block, star, graft, comb, and especially dendritic structures-offer unique advantages [35]. Dendritic macromolecules provide exceptional design flexibility for creating specialized structures with tailored properties [35]. Metabolic intermediates such as fumaric acid, citric acid, succinic acid, and pyruvic acid, along with monomers from clinically established polymers like poly (ethylene glycol) (PEG), poly(caprolactone) (PCL), and poly (trimethylene carbonate) (TMC), serve as ideal building blocks [35]. These can be strategically combined to create precisely engineered polymers for therapeutic applications, often by incorporating specific structural voids within dendritic architectures. Poly (glycerol succinate) (PGSu), a polyester synthesized from glycerol and dicarboxylic acids like succinic acid, represents one such example [35].

PGSu is produced through the polycondensation of two bio-based monomers: glycerol (a major biodiesel byproduct, with over two million tons of bioglycerol produced in 2012) and succinic acid (produced industrially from biomass fermentation) [36]. The synthesis employs bulk polycondensation without solvents or catalysts, generating no hazardous waste [36]. PGSu can form hyperbranched, highly branched, dendrimer-like, or branched architectures [36]. The mechanical and physical properties of these highly branched polyesters (HBPEs) are significantly influenced by synthesis conditions-including molecular weight, cross-linking density, and branching degree-while the molar reactant ratio determines the hydroxyl-to-carboxyl group ratio, ultimately defining whether liquid or gel forms are obtained [36]. Succinic acid production follows two primary pathways: petrochemical and biological routes [37,38].

Petrochemical methods include: (1) paraffin oxidation followed by succinic acid separation; (2) catalytic hydrogenation of maleic acid or maleic anhydride; (3) electrochemical synthesis of maleic anhydride; and (4) production from acetylene, carbon monoxide, and water using [CO(CO) 4] under high-pressure acidic conditions [38]. Electrochemical synthesis is particularly advantageous due to its high yield, low cost, high product purity, and minimal waste generation, making it suitable for food and pharmaceutical applications [38]. The production of succinic acid from renewable feedstocks has gained significant attention due to rising petroleum costs, dwindling reserves, and its potential conversion into valuable industrial chemicals like 1,4-butanediol. Numerous bacteria naturally produce succinic acid as a metabolic intermediate, and it appears among the fermentation byproducts of Saccharomyces cerevisiae alongside glycerol, lactic acid, and acetic acid. Achieving industrially viable production requires developing microbial strains capable of accumulating high succinate concentrations to enable economically feasible recovery [39-41].

Poly (Glycerol-Succinate)

Poly(glycerol-succinate) oligoesters (PGSs) are hydrophilic compounds that can be functionalized with hydrophobic alkyl chains to form amphiphilic structures [30,39,35]. Certain amphiphilic dendrimers have demonstrated effective antibacterial properties, making these alkylated oligoesters particularly interesting as potential surfactants [30,39,35]. Unlike conventional amphiphilic oligoesters that are typically copolymerized with petrochemical-derived groups such as polyethylene oxides, these branched PGS derivatives are entirely bio-sourced and exhibit anionic character [30,39,35]. Recent years have witnessed rapidly growing interest in green hyperbranched polyesters (HBPEs) as sustainable material alternatives [30,39,35]. HBPEs derived from renewable biomonomers show promise as plasticizers due to their molecular migration capability within polymer matrices combined with their eco-compatibility [35].

The significant attention toward HBPEs stems from their unique architectural features, including numerous terminal functional groups, remarkable stability, excellent solubility, and straightforward synthesis methodologies [35]. The distinctive plasticizing properties of these materials are primarily attributed to the presence of molecular-scale free-volume cavities [35]. Several bio-based HBPE systems have been developed, including poly (glycerol adipate), poly(glycerol-co-diacid), poly (glycerol succinate) (PGSu), poly(glycerol succinate-co-maleate), and poly (glycerol sebacate), supporting the advancement of contemporary bio-based materials for diverse applications [35]. PGSu represents a specific example of polyesters synthesized from glycerol and dicarboxylic acids such as succinic, sebacic, or adipic acid [35,42-46,30]. This polymer is formed through the combination of two bio-based monomers: glycerol-a significant byproduct of the biodiesel industry with production exceeding two million tons of bioglycerol in 2012-and succinic acid [35,42-46,30].

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PGSu has demonstrated utility as an accelerator for poly(caprolactone) degradation by facilitating moisture penetration into hydrophobic networks [42-46,30]. When conjugated with fatty alkyl chains, hydrophilic PGSu oligomers function as polar head groups that drive the formation of amphiphilic structures suitable for surfactant applications [42-46,30]. PGSu can serve as a bio-based surfactant in various consumer products including kitchen cleaners, body washes, and shampoos, potentially reducing the damage caused by synthetic detergents to skin and hair [42-46,30]. Notably, PGSu shares significant similarities with poly (glycerol sebacate), another glycerol-based polyester widely recognized in tissue engineering that has been proposed as scaffold material or scaffold additive for corneal, cardiac, bone, cartilage, and nerve tissue applications [42-46,30]. The synthesis of dendrimeric PGSu involves the reaction between succinic acid and benzylidene acetal, which serves as a protected form of glycerol [10]. This methodology employs a multi-step approach involving reaction of the protected monomer followed by deprotection, enabling repetition of the process to build dendritic architectures [10].

Poly (Glycerol-Succinic Acid)-Based Elastomeric Composites

Alpha-beta polyesters are widely used in pharmaceutical, environmental, and biological applications due to their excellent biodegradability and cost-effective manufacturing. Recently, star and hyperbranched polyesters derived from glycerol and diacids like succinic acid have garnered significant interest, particularly as the U.S. Food and Drug Administration (FDA) recognizes these bio-based diacids and glycerol as safe compounds [47].

Research into PGSu-based composites has demonstrated their versatility across various applications:

Composite Fabrication and Enhanced Properties:

- **Fibers for Medical Applications:** Dorota et al. [] utilized a synthesized glycerol succinate (PGSu) oligomer as an additive for poly (L-lactic acid) (PLLA) and poly(L-lactide-co-caprolactone) (PLCL) to produce biocompatible fibers. The study found that PGSu improved chain mobility in semicrystalline PLCL, increasing the crystallinity of the bicomponent fibers compared to pure PLCL. The mechanical properties of these fibers were influenced by the PGSu content and the crystallinity of the main polymer component. In vitro studies with L929 cells confirmed the biocompatibility of all bicomponent fibers [36].

- **Toughened Polymer Blends:** To address the brittleness of poly (lactic acid) (PLA), blends with poly (glycerol succinate-co-maleate) (PGSMA) were created using dynamic vulcanization during reactive extrusion. The cross-linked PGSMA particles within the PLA matrix promoted shear yielding, significantly enhancing tensile toughness. The 60/40 PLA/PGSMA blend showed a 53% improvement in elongation at break and a 175% increase in notched Izod impact strength compared to neat PLA [49].

- **Stable Thermoplastic Composites:** Valerio et al. [49] developed stable thermoplastic composites from PGSMA, PLA, and poly (butylene succinate) (PBS). A specific blend with a 35/40/25 PGSMA/PLA/PBS ratio demonstrated a tensile strength of 33.8 MPa, a tensile modulus of 1.47 GPa, and a notched Izod impact of 159 J/m, properties comparable to some commercial polypropylene products [50].

Material Enhancement for Specific Functions:

- **Bone Tissue Engineering:** Nakiou et al. [] investigated a new polypolyester (PGSuc) as a coating for mesoporous bioactive nanoparticles (MSNs) to create hybrid scaffolds for bone tissue generation. Initial results showed that coatings with and without MSNs improved the physicochemical properties of bioactive glass scaffolds and enhanced Alkaline Phosphatase (ALP) activity and alizarin red staining, indicating potential for osteogenic differentiation when cultured with adipose-derived mesenchymal stem cells [47].

- **Tuning Degradation and Mechanical Properties:** Farjaminejad et al. enhanced the degradability of poly (glycerol sebacate) (PGS) by incorporating succinic acid, which introduced more carbonyl groups and facilitated water absorption into the polymer structure [48]. In another study, the addition of PGSu and nanohydroxyapatite (n-HA) to a polycaprolactone (PCL) matrix improved its hydrophilicity and mechanical performance. The Young's modulus of PCL/PGSu-based scaffolds could be tuned from 11.5 MPa down to 4.5 MPa by varying the concentrations of PGSu and n-HA. Furthermore, coating these scaffolds with polypyrrole (PPy) introduced electrical conductivity ($\sim 5x10^{-2}$ S/cm) and desirable antibacterial activity, making them suitable for various tissue engineering applications [52].

- **Antimicrobial Scaffolds for Skin Regeneration:** A three-dimensional (3D) printable copolymer, polycaprolactone-block-poly (1,3-propylene succinate) (PCL-PPSu), was designed and incorporated with antimicrobial silver particles. The resulting scaffolds were characterized by a low processing temperature, enhanced degradation behavior, and adaptability to 3D printing, presenting a promising biomaterial for developing skin regenerative therapies [51].

Advanced Nanocomposites and Copolymerization:

A study proposed new biomaterials from succinic acid, glycerol, sebacic acid, and ε-caprolactone, creating bio-nanocomposites with n-HA and organomontmorillonite (C30B). The incorporation of succinic acid and ε-caprolactone increased chain mobility, reducing the glass transition temperature (Tg) of the base polymer. The addition of ε-caprolactone notably impacted tensile strength and Young's modulus. Hydrolytic degradation tests confirmed that succinic acid monomer improved degradability by absorbing water molecules, and the combination of C30B and n-HA nanoparticles further positively influenced the degradation rate [48] (Table 2).

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Conclusion

Biodegradable elastomeric polymers have garnered significant interest as advanced materials for biomedical applications, including tissue engineering and implantable drug delivery systems, owing to their superior mechanical properties, biocompatibility, and controlled degradability. Numerous elastomeric systems, such as poly (glycerol sebacate) (PGS), poly (polyol sebacate) (PPS), poly(diol-co-tricarballylate) (PDT), and tri-acrylic-poly(ε-caprolactone-co-d,l-lactide) cyclic ester (ASCP) derivatives, have been successfully developed to meet these demands. A review of the literature on poly (glycerol-succinic acid)-based elastomers specifically demonstrates that incorporating succinic acid effectively softens the polymer network by enhancing chain mobility and reducing the glass transition temperature (Tg). Furthermore, its hydrophilic nature promotes water absorption, which can modulate the degradation profile and appears to play a beneficial role in stimulating cellular differentiation and function.

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How to cite this article: Pardis Yousefi T, Reyhaneh T. Synthetic Elastomeric Scaffolds Based on Poly (Glycerol-Succinic Acid) for Tissue Engineering: A Review. Curr Trends Biomedical Eng & Biosci. 2025; 23(4): 556122. DOI: 10.19080/CTBEB.2025.23.5560122

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DOI: 10.19080/CTBEB.2025.23.5560122

How to cite this article: Pardis Yousefi T, Reyhaneh T. Synthetic Elastomeric Scaffolds Based on Poly (Glycerol-Succinic Acid) for Tissue Engineering: A Review. Curr Trends Biomedical Eng & Biosci. 2025; 23(4): 556122. DOI: 10.19080/CTBEB.2025.23.5560122