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Emerging Renewable Polymer Platforms for Biomedical Interfaces, Bioadhesives, and 3D Printing

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Abstract

The traditional polymer industry, which depends heavily on fossil resources, faces increasing challenges due to resource depletion, environmental damage, and sustainability issues linked to petroleum-based materials. In response, the development, synthesis, and regeneration of eco-friendly, renewable bio-based polymers have gained significant attention from both science and industry as promising alternatives. In addition to reducing the negative environmental impact of conventional plastics, biodegradable and renewable polymers now play a crucial role in enabling advanced biomedical functions, particularly at biological interfaces. Recent advances have highlighted bioadhesive systems as a crucial subset of renewable polymers, enabling effective interactions between materials and biological tissues under physiologically relevant conditions. These bioadhesive materials, made from natural synthetic bio-based, or hybrid polymer platforms, are increasingly used in biomedical applications such as wound closure, tissue sealing, implant fixation, drug delivery, and biofabrication. At the same time, integrating biodegradable polymers and bioadhesive formulations into three-dimensional (3D) printing technologies improves process efficiency, material accuracy, and design flexibility while reducing waste and environmental impact. This review critically examines emerging renewable polymer platforms, with a focus on bioadhesive systems, biodegradable polymers, and additive manufacturing techniques. The discussion includes the benefits, limitations, recent advances, and future outlook of these materials within the context of sustainable biomedical interfaces and 3D-printed structures. By offering an integrated view, this work underscores the transformative potential of renewable polymer-based bioadhesives and 3D printing in advancing next-generation biomedical engineering while promoting circular and sustainable material practices. This manuscript provides a comprehensive narrative review of emerging renewable polymers for biomedical interfaces, bioadhesives, and 3D printing.

Keywords: Emerging polymers; bioadhesives; biomedical engineering; 3D-printing; sustainable developments.

I. INTRODUCTION

Renewable polymers from natural resources like plants, algae, and microorganisms provide a sustainable alternative to conventional polymers derived from fossil resources. As environmental concerns gain international attention, industries are looking for materials that not only satisfy performance standards but also support sustainability objectives. Many of the answers to the increasingly complicated issues brought on by climate change depend on chemistry and developments in sustainable science, ranging from cleaner agrochemicals and improved medications to novel materials and greener energy sources. By creating lucrative products with fewer harmful and dangerous byproducts, sustainable chemistry aims to advance industrial chemistry. We focus on three primary areas to improve chemical scholarship: research that advances fairness and equality, chemistry itself, and sustainability in laboratory operations. Novel renewable polymers have been developed because of recent technological developments. To improve material qualities and processing efficiency, methods like genetic engineering and nanotechnology are being used. To directly compete with traditional materials, future research may concentrate on improving the qualities of renewable polymers and increasing the scalability of their manufacturing.

When properly designed, these materials may take on almost any shape, which is advantageous when new structures need to be created to support or restore the body's systems to their normal functioning [1]. The creation of bio-composites, the discovery of hitherto undiscovered capabilities, and the creation of novel substance entities are the results of intensive studies that can further assist medical professionals in their work in tissue regeneration, diagnosis, and therapy. Renewable polymers have great potential to revolutionize industrial applications by providing a viable approach to achieve performance requirements while lowering environmental effects. To realize their full potential, supportive legislation, commercial acceptability, and ongoing research and development are essential. Industries may significantly contribute to the transition to a more sustainable future by using renewable polymers.

Meanwhile, in a world battling a shortage of food, researchers need to leverage the abundance of inedible biomass resources to minimize the diversion of important food and to facilitate industrial output. The most abundant components are cellulose and lignin, which are typically wasted and misused. Furthermore, Castor oil, tung oil, and turpentine are examples of non-edible oils that are commonly used in fuels, plasticizing agents, coatings, grease, and surfactants [2]. To address the resource waste and adverse environmental effects of the conventional polymer preparation process, biomass has been utilized as an initial precursor to develop recyclable polymers for biomedicals.

In many industrial areas, finding sustainable materials is a global concern. Their mechanical characteristics significantly influence the performance of materials. The rapid Technological developments in 3D printing have sped up the creation of new sustainable biomaterials [3]. Even though various metal materials are utilized in contemporary additive manufacturing or 3D printing processes, these efforts are mostly restricted to polymers or plastics. Using appropriate bio-renewable resources in their place, bio-composite materials seek to mitigate the shortages of mineral and petroleum-based components. The main sources of sustainable materials are bio-renewables, which include natural fibers, biopolymers, and other materials derived from biomass. However, their uses have been restricted due to their intrinsic flaws, which include low strength, high hydrophilicity, and poor compatibility [4].

3D printing, an additive technique, has emerged as a viable tool for manufacturing technical parts, in contrast to conventional manufacturing methods [5]. Moreover, 3D printing has facilitated the development of new designs, including biomimetic structures, by enabling the rapid modification of composite materials [6]. Among the principal drawbacks caused by the industrialization of society has been harm to the ecosystem, which has raised attention to the need for sustainable methods and approaches [7-9]. The schematic in Fig. 1 highlights the three core focus areas of this review: (i) development of renewable polymer platforms from natural resources, (ii) evolution of bioadhesive systems for tissue interfacing and medical integration, and (iii) incorporation of these materials into 3D printing technologies for patient-specific biomedical designs. The framework emphasizes circular sustainability through recyclable materials, reduced environmental impact, and closed-loop processing.

A. Bioadhesives: Definition, Classification, and Relevance to Renewable Polymers

Bioadhesives are a class of adhesive materials derived wholly or partially from biological or bio-based sources and are designed to form effective bonds with biological tissues or substrates under physiological or environmentally benign conditions. Unlike conventional petrochemical-based adhesives, bioadhesives emphasize biocompatibility, biodegradability, and reduced ecological footprint, making them particularly attractive for biomedical and sustainable manufacturing applications.

Bioadhesives can be broadly classified into natural bioadhesives (e.g., polysaccharide- and protein-based systems such as starch, cellulose, chitosan, gelatin, and fibrin), synthetic bio-derived adhesives (e.g., polyesters, polyurethanes, and modified poly (lactic acid)), and hybrid bioadhesive systems that integrate bio-based polymers with functional modifiers to enhance adhesion strength, durability, and stimuli responsiveness.

The renewed interest in bioadhesives is driven by increasing demand for minimally invasive medical devices, tissue adhesives, wound closure systems, drug-eluting scaffolds, and biofabrication inks for 3D printing. In these contexts, renewable polymers serve not only as structural matrices but also as active adhesive components capable of interacting with biological surfaces through hydrogen bonding, electrostatic interactions, covalent crosslinking, or bio-inspired mechanisms.

Within the broader framework of emerging renewable polymers, bioadhesives represent a critical functional subset that connects sustainability objectives with advanced biomedical performance. Their integration with biodegradable polymers, conductive polymer systems, and additive manufacturing platforms underscores their growing role in next-generation biomedical engineering and circular material design.

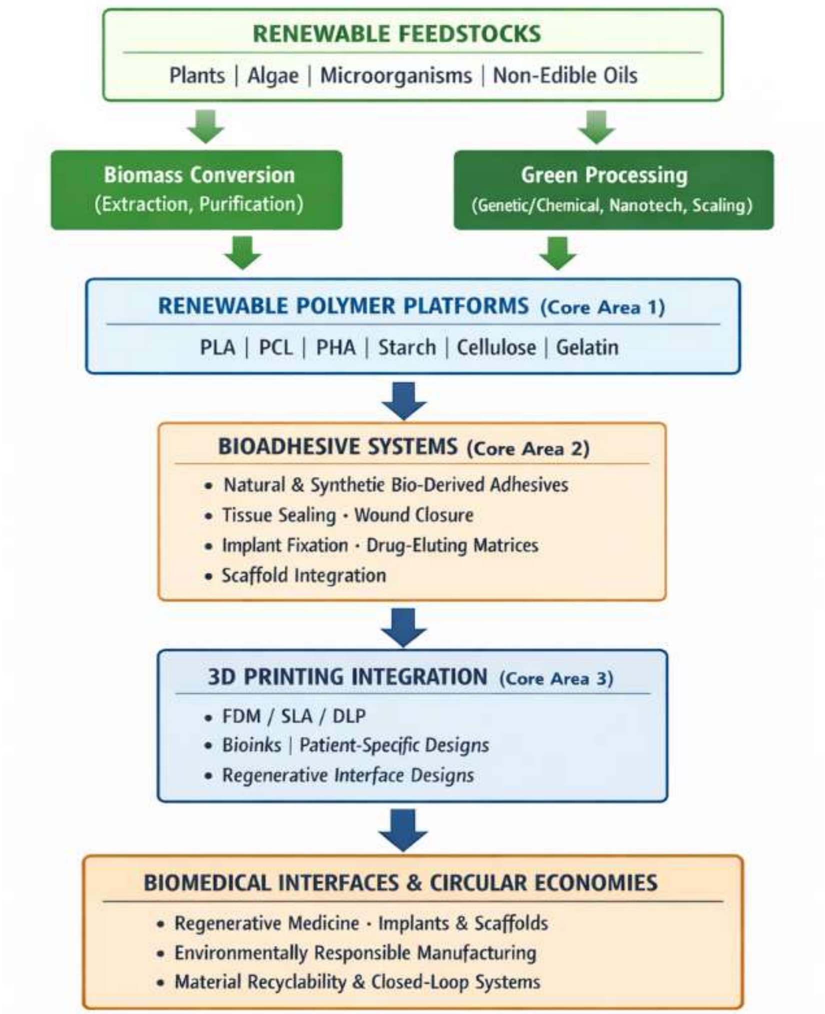

Fig. 1. Conceptual pathway illustrating the transition from renewable biomass feedstocks to biomedical and additive manufacturing applications.

II. APPLICATIONS AND IMPLEMENTATIONS OF CLOSED-LOOP RE-USABLE POLYMERS

Plastic's widespread use as a representation of today's technologically sophisticated society has resulted in the massive consumption of limited and non-renewable fossil fuels. In contrast to their thermoplastic equivalents, thermosets are distinguished by covalent intermolecular chemical cross-links, which enhance rigidity and strength and lessen creep. They evolve into being less vulnerable to heat and chemical shocks from their surroundings as a result, making them ideal for implementation in shielding and functional (composite) systems (such as turbine blades and aerospace products). However, thermosets are extremely challenging for disposal due to their excellent mechanical and thermal resilience. Formaldehyde, epoxy resins, alkyd compounds, isocyanates, and conjugated polyesters are the main classes of thermoset resins. Bonding (functional) fragments and reinforcing threads produce lightweight yet strong substances after curing; these are typically used as multicomponent responsive formulations [10]. Because of the covalent cross-links that give them their mechanical strength, chemical resistance, and thermal stability, cross-linked polymers are used in car parts, automobile tires, insulating properties, adhesives, and a myriad of other items.

With the benefit of streaming services, chemical breakdown through depolymerization or disulfide decrease, polymers made from bio-based compound α-lipoic acid (also known as lipoate) are regarded as attractive possibilities for sustainable alternatives [11-13]. Reference [13] investigated the de-polymerization dynamics of poly-(ethyl lipoate) (PEtLp) under various conditions, and discovered that they are highly dependent on the pKa values. Remarkably, over a two-day period at 25 ˚C, PEtLp in chloroform or toluene (20 mg/mL) exhibited complete de-polymerization (100% conversion) back to the original EtLp in the presence of tri-fluoro-acetic acid (TFA). To enable self-sustained repetitive chemical recycling, a closed-loop reusable polymer hybrid was manufactured that completely breaks down into a solution, comprising a monomer, a crosslinker, and conductive fillers like nanotubes of carbon nanotubes (CNT). Similarly, [2] presented the latest developments in closed-loop reusable bio-based polymeric components, primarily from the perspectives of applications, creative design techniques, and starting materials, and it also included a forecast for their continued development as revealed in Fig. 2.

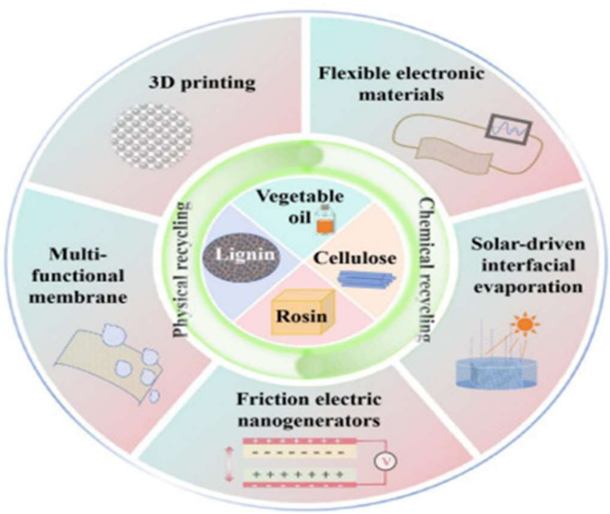

Fig. 2. Applications for reusable and biodegradable polymer components generated from renewable energies [2].

A closed-loop recyclable polymer can be depolymerized into pure, well-defined monomers and subsequently re-polymerized into materials that retain comparable performance characteristics [14]. Owing to this regenerative capability, such systems have attracted significant interest from both academia and industry and are widely regarded as a promising pathway for the future development of biodegradable polymers.

In this context, [15] reported the production of a closed-loop epoxy–amine thermoset derived entirely from renewable resources, with the objective of achieving high material performance while enabling recyclability. The approach relied on molecular-level design strategies incorporating regenerable building blocks and cleavable linkages within the polymer backbone. Specifically, 4,4′-methylene bis(cyclohexylamine) (MBCA) was isolated from industrial lignin side streams and demonstrated to function effectively as a bio-derived curing agent for high-performance polybenzoxazine and epoxy–amine thermosets.

To achieve closed-loop recyclability, epoxy–amine thermosets based on diglycidyl esters of 2,5-furandicarboxylic acid and terephthalic acid (DGF and DGB, respectively), in combination with selected reference amines, were investigated in place of conventional bisphenol-based diglycidyl ether systems [15]. This design strategy illustrates how renewable feedstocks and tailored molecular architectures can be combined to produce recyclable thermosets with competitive mechanical and thermal properties.

A. *Bioadhesive Systems in Biomedical Interfaces*

Bioadhesive systems constitute a critical functional class of biomaterials designed to establish and maintain intimate contact between synthetic materials and biological tissues. In biomedical interfaces, bioadhesives enable effective bonding under physiologically relevant conditions while minimizing tissue damage, inflammatory response, and long-term toxicity. Their relevance has grown significantly with the increasing demand for minimally invasive medical procedures, implantable devices, and tissue-engineered constructs derived from renewable polymer systems.

Bioadhesives operate through a combination of interfacial mechanisms, including hydrogen bonding, electrostatic interactions, covalent crosslinking, and bio-inspired adhesion strategies [16]. These interactions allow bioadhesive materials to conform to dynamic, hydrated, and irregular biological surfaces such as skin, mucosa, bone, and internal organs. Unlike conventional medical adhesives that often rely on cyanoacrylate or petroleum-derived chemistries, bioadhesive systems based on renewable polymers prioritize biocompatibility, controlled degradation, and reduced environmental impact.

Natural polymer-based bioadhesives, including those derived from polysaccharides (e.g., starch, cellulose, chitosan, and alginate) and proteins (e.g., gelatin, fibrin, and collagen), have attracted considerable attention due to their inherent bioactivity and biodegradability. These materials can promote cell adhesion, proliferation, and tissue integration while serving as temporary fixation agents or delivery platforms for therapeutic molecules. However, their relatively weak mechanical strength and sensitivity to moisture often necessitate chemical or physical modification to enhance adhesion performance and stability.

Synthetic and semi-synthetic bioadhesives derived from renewable monomers, such as polylactic acid (PLA), polycaprolactone (PCL), and bio-based polyesters, offer improved tunability in terms of mechanical properties, degradation kinetics, and interfacial bonding strength.

Through functionalization strategies such as the incorporation of catechol groups, ester linkages, or dynamic covalent bonds, these materials can achieve strong yet reversible adhesion suitable for wound closure, tissue sealing, and implant fixation. Hybrid bioadhesive systems that integrate natural polymers with synthetic backbones further expand the design space, enabling the optimization of adhesion, elasticity, and biological response.

In advanced biomedical interfaces, bioadhesives increasingly serve multifunctional roles beyond mechanical attachment. They act as matrices for controlled drug release, electrically active interfaces in bioelectronic devices, and printable bio-inks for additive manufacturing of tissue scaffolds. The convergence of bioadhesive chemistry with biodegradable conducting polymers and 3D printing technologies enables the fabrication of patient-specific constructs with enhanced interfacial stability and functional integration [15-18].

Despite significant progress, challenges remain in balancing adhesion strength, degradation behaviour, and long-term biocompatibility. Factors such as wet-surface adhesion, immune response, and scalability of bioadhesive formulations continue to limit clinical translation. Addressing these challenges through molecular design, sustainable feedstock selection, and processing innovation will be essential for advancing bioadhesive systems as integral components of next-generation biomedical interfaces.

Fig. 3 presents a schematic overview of bioadhesive material classes (natural, synthetic bio-derived, and hybrid systems), their dominant interfacial adhesion mechanisms, including hydrogen bonding, electrostatic interactions, covalent and dynamic crosslinking, and bio-inspired adhesion, and their key biomedical applications. These applications span wound closure and tissue sealing, implant fixation and coatings, drug-eluting adhesive matrices, bioelectronic interfaces, and 3D-printed bioadhesive scaffolds, illustrating how renewable polymer feedstocks support biocompatibility, controlled biodegradation, effective wet-surface adhesion, mechanical compliance, and sustainability at biological interfaces.

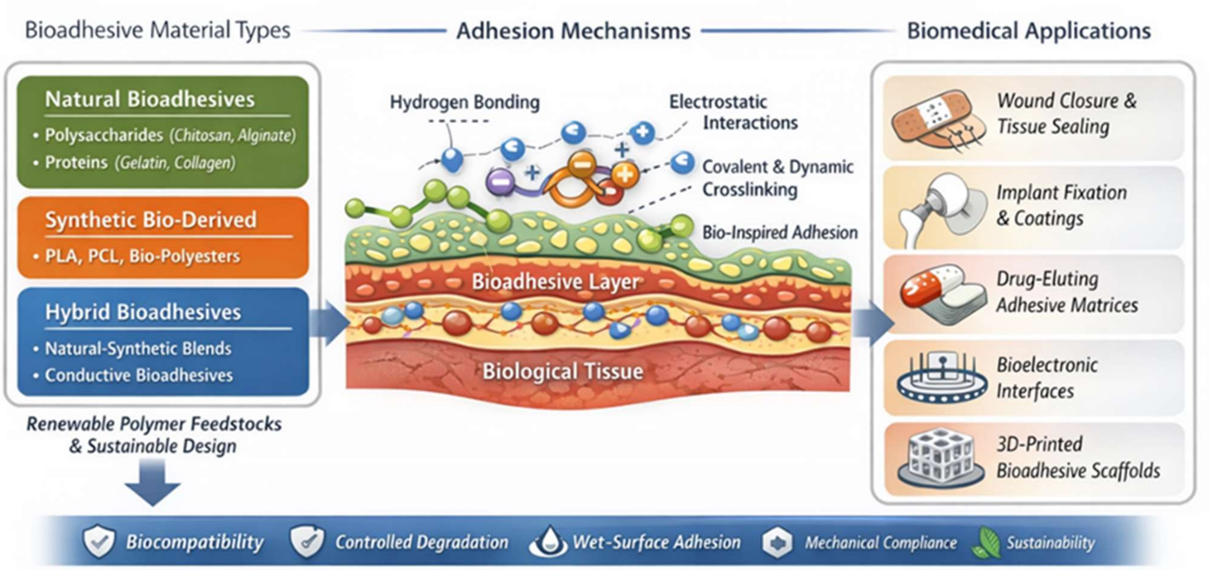

Fig. 3. Bioadhesive systems in biomedical interfaces derived from renewable polymer platforms.

1) Biomedical Applications

Biodegradable plastics are a new field of study [19-22]. The goal of biodegradable plastics is to reduce environmental impact and create a cleaner and greener planet [21]. Particularly in biomedical applications, polymers are of tremendous interest due to the startling rise in the number of diseases and ailments that have been diagnosed. Biodegradable polymers are increasingly being used in biomedicine [1].

With such stringent requirements, such as total breakdown to prevent polymer remains in the human system, nontoxicity of polymer compounds and degraded products, and other appropriate qualities, the novel degradable polymers for applications in medicine are difficult to develop. Reference [23] was able to show a range of degradable polymers made via sequential co-polymerization of Schiff bases and cyclic anhydrides for medication utilization. The copolymerization is flexible and catalyst-free, allowing to production of polymers with In-chain peptoid and ester groups, cyclic topologies, and other common feedstocks. Unlike the other degradation methods, the polymers show self- and auto-degradation without any stimulus. The nature of the polymer and ambient temperature greatly influence the degrading performance, which can range from a few hours to several months. The polymers' distinct qualities have led to their approval for use in biomedical systems, as proven by reliable in vitro and in vivo drug release as well as cell survival assays [23]. Fig. 4 shows the application of a copolymerizing agent as a carrier substance for sustained drug release.

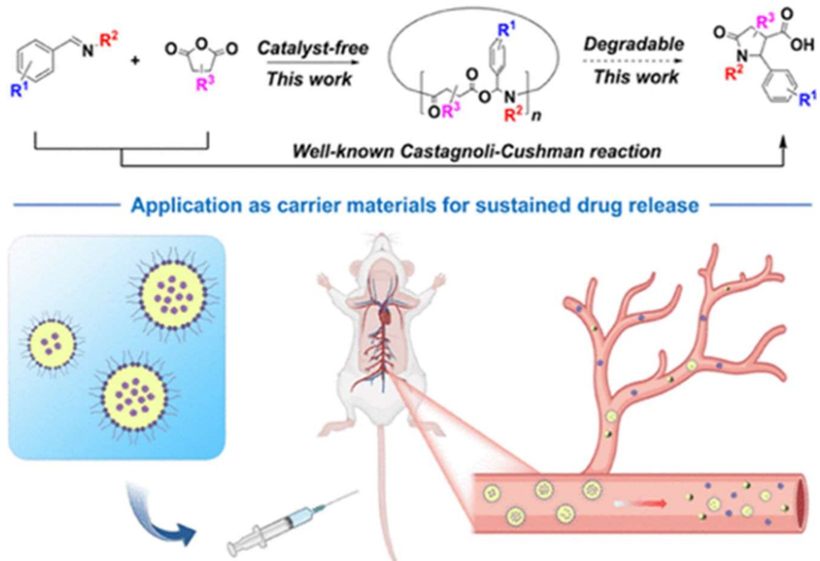

Fig. 4. Schiff bases and cyclic anhydrides copolymerize alternately as carrier compounds for prospective drug release [23].

Polylactic acid and polyhydroxyalkanoates (PHA), two of the latest promising renewable polymers, have drawn attention as possible substitutes for current procedures [24], given their ability to be synthesized from non-toxic, sustainable feedstocks. Polylactic acid's moldability enables it to take on a variety of shapes, including scaffolding, fibers, and micro- and nanostructures [25]. Because of its qualities, including durability, decomposition, and biocompatibility, considering processing, PLA has emerged as a key polymeric material with medical uses. Lactic acid (LA) can be created by fermented sugars derived from natural sources, such as sugarcane and wheat. Consequently, PLA is a safe, eco-friendly polymer with qualities that enable its application in human tissues of humans. PLA has many uses, but it also has drawbacks, including a slow rate of disintegration, low-impact hardness, and hydrophobicity. Combining PLA with other polymers provides easy ways to enhance related qualities or create new PLA polymers or blends for specific uses.

Numerous PLA blends are studied for use in biomedical applications, including implants, stitches, and drug delivery [26]. The in situ LA extractive fermentation method will simplify further processing and turn out to be a more cost-effective and sustainable choice [27]. Fig. 5 presents a graphical abstract of the characteristic applications of PLA in medicine.

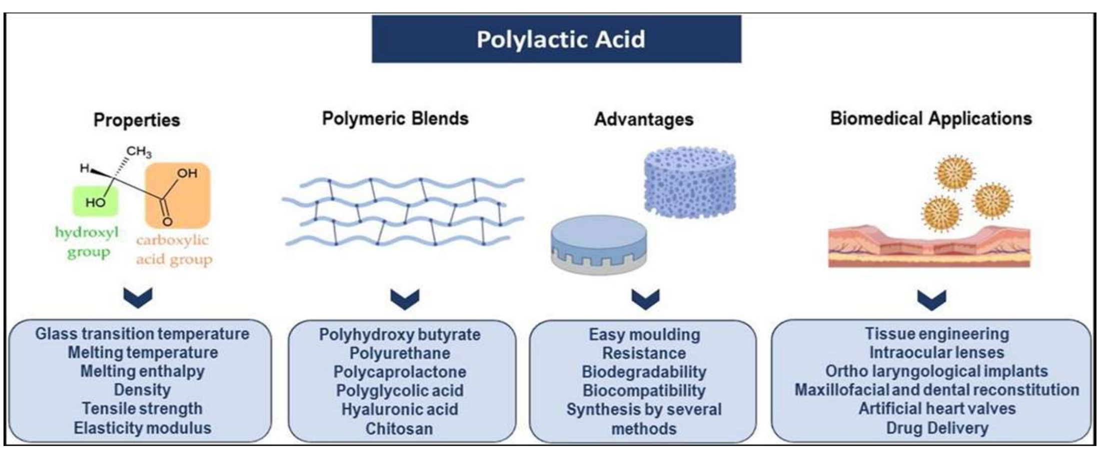

Fig. 5. Characteristic biomedical applications of polylactic acid [25].

Medically, polyesters made from lactic acid enantiomers are thoroughly investigated for application in a range of equipment [2]. These environmentally friendly substances are printed in three dimensions (3D) and used in functional therapeutic settings like medication delivery methods, tissue engineering, implantable devices, and dressings [28].

Biodegradable resins made from polyester are finding applications in many industries, like electronics, medicines, packaging for foods, orthopedics, skincare products, textiles, and vehicles [29-30]. Amid an array of plastics that biodegrade, in addition to being commercially accessible, polylactic acid is environmentally friendly and may be broken down after use in terms of numerous characteristics appropriate for industrial use, including mechanical, physical, biocompatibility, and processability. PLA is comparable to other conventional plastics like PP and PET. These characteristics have made PLA the most popular biopolymer in several sectors, such as packaging, automotive, and agricultural [31]. Biosensing, immunotherapy, drug transport, tissue engineering and regeneration, implants, and medical devices are just a few of the biomedical fields that make extensive use of biopolymers [32].

Biomedical polymeric substances are at the forefront of medical developments, providing novel approaches to disease prevention, diagnosis, treatment, and therapeutic usage due to their remarkable physicochemical characteristics [32-36]. The use of gelatin in many biomedical research applications has increased due to developments in imaging technology, mechanobiology, plastic chemistry, and 3D biofabrication methods. These applications range from wound closure and chemotherapy for cancer to cartilage tissue engineering.

Reference [37] presented the most recent developments in gelatin-based techniques in tissue engineering and drug administration using biomaterials, along with some of the most pertinent difficulties and restrictions, while [38] emphasized the advancements of the use of biodegradable polymeric materials for pharmacological programs, for example, in delivery systems for controlled drug dispensing. The demand for special and distinctive materials has risen because of emergent diseases, medical technology advancements, and the necessity for prompt and efficient therapies. Polymers, metals, and ceramics are used to create many materials in different shapes, sizes, and forms that have been thoroughly investigated in both in vitro and in vivo settings. Metals, polymers, and ceramics are examples of biomaterials employed inside the body as scaffolds, implants, medication, or carriers of genes and protective agents. Biomedical products can be made from materials; organic polymers are preferred over metallic ones due to their superior biocompatibility and capacity to break down in vivo without generating harmful compounds [39]. Since PMMA is inexpensive, biocompatible, and easy to process, it is frequently utilized in orthopedic systems, such as bone cement, bone padding, and substitute bones in complete joint replacement surgery. However, because PMMA is non-bioactive, has poor osseointegration, and is not biodegradable, its capacity to regenerate bone is restricted. Also, there are disadvantages to using bone cement, including the release of methyl methacrylate (MMA) and the possibility of thermal necrosis due to the high exothermic temperature during PMMA polymerization. Methods for transforming surfaces and the addition of different bioactive agents and biopolymers to PMMA are two of the strategies that have been used to address these issues [40].

Porous organic polymers (POPs) have emerged as a distinct and rapidly advancing class of functional polymeric materials. In recent years, considerable research attention has been devoted to the design and development of POPs, particularly with a focus on biological and biomedical applications. An overview of the principal POP subclasses, together with their synthetic strategies and functionalization approaches, underscores their remarkable structural diversity and broad application potential.

POPs constitute highly versatile platforms for biomedical use, owing to their intrinsic porosity, modular design, and chemical robustness. Recent advances have demonstrated their utility across a wide spectrum of biomedical applications, including drug delivery, biomacromolecule immobilization, photodynamic and photothermal therapy, biosensing, bioimaging, antibacterial activity, and bioseparation [41]. These capabilities arise from the ability to precisely tailor their pore architecture and surface chemistry to accommodate specific biological functions.

Within the broader field of porous materials, POPs represent a rapidly growing research frontier. They are multidimensional porous network materials constructed from organic building blocks with defined geometries and morphologies, interconnected through strong covalent bonds [42]. This molecular-level design confers exceptional stability and structural integrity while enabling fine control over network topology. Also, they have attracted increasing interest due to their wide-ranging applications in energy storage and conversion, chemical and biological sensing, photoelectric devices, heterogeneous catalysis, and gas storage and separation [43–44]. Their advantages include inherent high porosity, low density, outstanding chemical and thermal stability, and predesignable yet tunable structures and functionalities. Through the incorporation of targeted functional building units, their pore structure, pore size distribution, specific surface area, and chemical functionality can be rationally engineered and precisely controlled [45].

To contextualize these materials within the landscape of renewable polymer systems relevant to biomedical interfaces, Table I provides a comparative summary of key performance metrics, degradation behaviors, and clinical applicability. These distinctions elucidate why biodegradable conducting polymers are increasingly being explored as functional alternatives in applications requiring electrical communication, signal transduction, or active interface performance.

Table I. Performance comparison of PLA, PCL, PHA, and gelatin-based bioadhesives in biomedical applications.

Polymer System	Biodegradation Rate	Mechanical Strength	Adhesion/ Interfacial Behaviour	Key Biomedical Uses	Major Advantages	Limitations	Reference
PLA	Slow–moderate (months–years)	High stiffness, low elasticity	Weak adhesion on wet tissue; surface modification is often required	Implants, sutures, scaffolds, 3D-printed components	Good printability; biocompatible; derived from renewable feedstocks	Brittle, hydrophobic; degradation may be too slow for some clinical timelines	[18]
PCL	Very slow (years)	Flexible, ductile	Moderate adhesion after functionalization	Long-term scaffolds, drug delivery systems	Excellent shape retention, flexible, compatible with FDM/AM systems	Very slow degradation; limited mechanical strength for load-bearing implants	[41], [46-47]
PHA	Moderate (weeks–months)	Strength varies by grade (PHA, PHB, PHBV)	Good tissue interaction; can be tailored chemically	Wound dressings, bioresorbable medical devices, sutures	Fully bio-based and biodegradable; tunable performance; low cytotoxicity	Thermal instability; inconsistent processing behaviour in 3D printing	[48-49]
Gelatin-Based Bioadhesives	Fast (days–weeks)	Soft, viscoelastic	Strong wet-surface adhesion; supports cell attachment	Tissue sealing, wound closure, drug-eluting matrices, bioinks	Excellent biocompatibility; supports cell growth		[16], [50]

B. Biodegradable Conducting Polymers

A novel family of biomaterials known as biodegradable conducting polymers combines the qualities of biocompatible (i.e., biodegradability) and conducting (i.e., electrical conductivity) polymers. They are a promising way to create cutting-edge materials that can control medication release, promote the growth or differentiation of distinct cell types, and activate desired tissue [51]. In the middle of the seventies, conducting polymers (CPs), a new class of organic components, were first created. In addition to having desirable qualities like ordinary polymers, like ease of synthesis and good processing ability in comparison to metals, CPs also share electrical and optical characteristics with inorganic semiconductors cum metals [52-53].

Reference [53] was able to use conductive pyrrole and thiophene molecules joined by ester bonds to create a conducting polymer, with the results revealing that the conducting polymer is biocompatible and biodegradable. Therefore, these conducting polymers can interface with tissue electronically.

Polyaniline (PANI), one of the many electrically conductive polymers, has drawn interest because of its special characteristics and doping chemistry. By adding renewable resources like cellulose, chitin, chitosan, etc. to the PANI framework, several electrically conducting recyclable polymers have been created. In addition, hybrid components are used in biomedical applications as batteries, sensors, antibiotics, and photocatalysts. Additionally, targeted drug delivery, dental restorations, and surgical tissue engineering use this renewable conducting polymer. The most recent developments in PANI-based polymers are reviewed, with synthesis methods and special applications in industries [54]. In the biomedical domains of neurological implantation, medication delivery systems, bio-actuators, biosensors, and scaffolding for tissue design, conductor-based polymers that possess excellent biological compatibility, such as polypyrrole, polythiophene, polyaniline, and its analogs (namely poly(3,4-ethylene-dioxythiophene) along with aniline oligomer, find extensive use [52].

An innovative interpenetrated polymer network (IPN) was created by electrochemically piercing a compostable hydrogel of poly (aspartic acid) (PASP) with poly (hydroxymethyl-3,4-ethylene dioxythiophene) (PHMeDOT) and a conductive polymer composite, poly (3,4-ethylene dioxythiophene) (PEDOT) [56]. To maximize the crystalline and electrolytic qualities, various proportions of cross-linker and PEDOT MPs were investigated, together with varying electro-polymerization durations. The fresh material is suitable for possible uses in biomedicine due to its properties, which include electrical conductivity, biocompatibility, bioactivity, and biodegradability [56].

The calcium-ion binding capacity, hygroscopicity, and water absorption properties of three different forms of enhanced poly (aspartic acid) were identified by Nakato et al. [57]: connected poly (aspartic acid) (6), alkylamine modified poly (aspartic acid) (5), and poly (aspartic acid-co-amino-carboxylic acid) (4). The type of amino carboxylic acid and its quantity in co-polymers determined the chelating calcium-ion capacity 4. With an Mw of 14000, the greatest value was three times that of poly (acrylic acid). Among homo-poly (aspartic acid) and improved poly (aspartic acid), the highly transformed PASP, such as 50 mol% lauryl amine modified poly (aspartic acid), exhibited excellent hygroscopicity. When poly (aspartic acid) hydrogel was made by irradiating homo-poly (aspartic acid) with γ-rays, the maximum swelling was found to be 3400g de-ionized water/g-dry hydrogel [57]. The periods of retention from gel-permeation chromatographic examination and the 1H NMR approach for estimating the length of the polymer chain were shown to correlate qualitatively [58].

Because biodegradable conducting polymers are naturally plastic and biodegradable, electrically conducting polymeric bio-nanocomposites (ECPBs) are currently receiving attention as components for biomedical, agricultural, and food technology. Conductive hydrogels (CH) are biomaterials used in tissue design that effectively replicate the physiologically and electrochemically inclined properties of human tissues [49], [59-61].

III. 3D PRINTING

The groundbreaking possibilities of three-dimensional printing cum automated learning with biopolymers, highlighting their critical role in promoting sustainable production and consumption in the years to come, and offering a path for future developments, have stirred research interest among researchers and industrialists [62]. The method of incorporating material into items is called additive manufacturing (AM). 3D printing, therefore, is a type of additive manufacturing. The process of making an object via the inclusion of material instead of removing it is known as additive manufacturing. Like 3D printing, additive manufacturing often requires CAD software and a machine. Following the instructions from the CAD application, the machine adds material to create the desired item [62].

Accelerated prototyping, also known as 3-D printing, layered manufacturing (additive manufacturing), is the process that quickly converts electronics to real-world scenarios. Polylactic acid (PLA), which has advantageous material qualities like nontoxicity, biological compatibility, and biodegradability, is one of the most widely used materials in AM. It is considered a leading biomaterial for various medical applications, including dentistry, where it can be utilized for tissue design and medical objectives in addition to dental models (education, training, and simulation demands) [6]. Several biodegradable polymers that can be used in 3D printers are shown in Fig. 6.

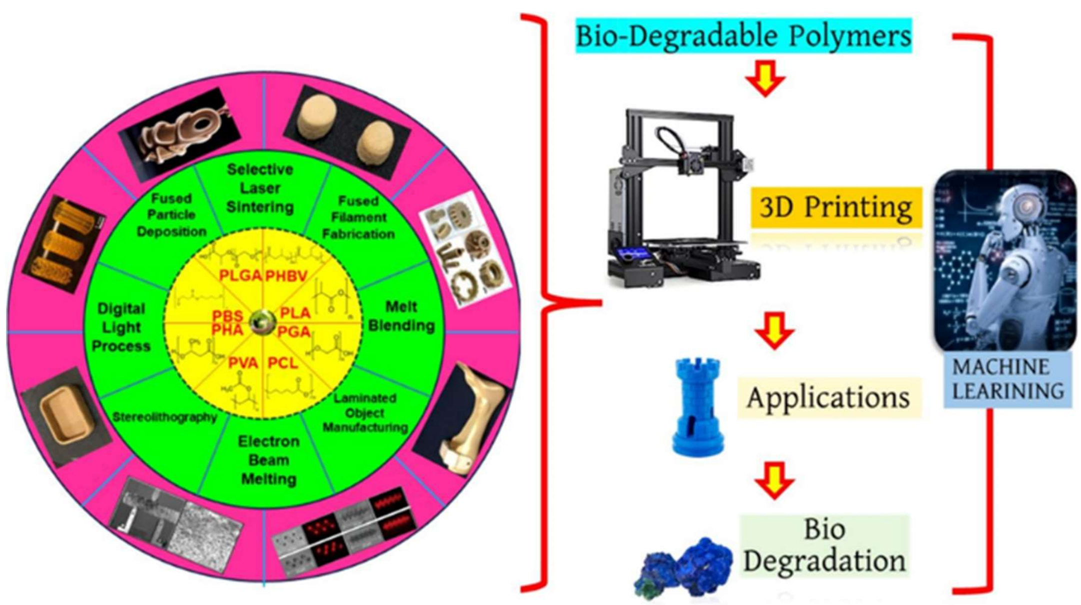

Fig. 6. 3D-printing biodegradable polymers [62].

Regarding the next wave of light-based 3D printing, material design is crucial in addition to the creation of novel technologies. Thermoset polymer systems connected by covalent bonds that cannot be broken are frequently produced by standard printable polymeric substances, most often photographic polymers or photo-resins. These materials offer poor re-processability and limited adaptability. Network rearrangement is made possible by dynamic connections that can be broken in reverse and rebuilt, giving the materials previously unheard-of qualities like flexibility, self-healing, and recycling potential. To meet the growing demands of environmentally conscious and nature-inspired designs (such as self-healing and adaptability) and to further broaden and meet the various use cases of 3D printed multi-functional materials, dynamic bonds are being introduced into materials over light-based 3D printing [63]. 3D printing, another name for additive manufacturing, is a rapidly expanding field that has the potential to support a circular and sustainable economy. Additionally, the manufacturing process offers a large range of materials and design freedom, which increases its use in the production of bioplastic parts. Because of this material flexibility, attempts have been made to create 3D printing filaments from bioplastics like Poly (lactic acid) to replace typical conventional plastic filaments derived from fossil fuels, like Acrylonitrile butadiene styrene [8], [64].

For a sustainable growth of the 3D printing business, the development of bio-based, recoverable photopolymers is essential for UV-curable 3D printing. For digitally processed light (DLP) 3D printing, [9] developed new reusable and re-printable castor oil (CO)-based photopolymers using hindered urea bonds, a separating dynamic covalent bond. The printed products could be recycled for 2 hours at 100 °C or 4 hours at 90 °C without the need for catalysts or solvents, which was unexpected. Based on their findings, the recycled resins also exhibited comparable physicochemical characteristics, kinetics of polymerization, and printing qualities of the starting resin. The authors utilized the best biobased resin to create thermochromic materials and re-printable sacrificial molds, which can be applied to intricate domains, including data cryptography and counterfeiting protection, as well as model casting. Thermochromic microcapsules might be reprocessed without causing any harm [9].

High rigidity and durability, exceptional adaptability, and a high ratio of surface area per volume are desirable mechanical features of cellulose nanocrystals (CNCs) [65]. Additionally, for upscale applications such as tissue engineering, actuation, plus biomedicine, the mechanical characteristics of CNCs can be customized chemically. Developing complex and elaborate geometries is greatly aided by modern manufacturing techniques, such as 3D/4D printing. The main advancements in additively built CNCs, which support environmentally friendly solutions for a variety of applications, are highlighted in this article. This paper also discusses the current issues and potential research paths for CNC-based composites made with 3D/4D printing methods. These include uses in robotics, wearable electronics, the engineering of tissues, wound treatment, and anti-counterfeiting measures [66-67].

Although Ecologists' adoption of this novel approach has been sluggish, three-dimensional (3D) printing offers a means of quickly producing both unique and identical objects that could be employed in ecological investigations. Reference [66] demonstrated that prototypes made from the less expensive and more ecologically friendly material (a 70% plastic and 30% repurposed wood fiber blend) were just as durable and had rates of predator attacks that were equivalent to those made utilizing the costliest material (100% virgin plastic) following evaluating two print media in the field [66]. Considering recent developments in less hazardous, biodegradable, and recyclable materials, environmentalists choose to reduce the negative effects of 3D printing while also saving time and money.

IV. CHALLENGES AND FUTURE PERSPECTIVES OF EMERGING POLYMERS

Product enhancements, cost reduction, and resource waste reduction can all be used to illustrate the difficulties. Additionally, it is crucial to consider other factors, including sustainability, when making various advances. Thus, there is a compelling need to step up efforts to create cutting-edge methods to address the various obstacles in this subject that integrate multiple research directions.

Plastic's widespread use as a representation of the technologically sophisticated society of today has resulted in the massive consumption of a limited and non-renewable matrix, which is not taken into consideration by these techniques, which usually ask for a substantial energy input. Instead, they concentrate on recovering the more valuable substrates, fillers, or fibers. Much academic research indicates prospective solutions that use dynamic covalent connections or degradable links to boost the circularity of thermoset goods while requiring less energy. Most of this research, nevertheless, has little chance of being used in industry. By concentrating on the following, this work seeks to close the discrepancy between advances in academia and industry: those that are most pertinent from an economic, sustainable, and technical perspective. Examples of potential applications that might soon hit the market are shown, along with a review of the methods now employed for recycling thermoset materials and the creation of innovative thermosets that are intrinsically recyclable [68].

Thermoplastics can also be made from macromolecules like starchy carbohydrates and cellulose in addition to renewable monomers. However, problems including hydrophilic hydroxyl groups and comparatively poor solubility may impair performance. A modification reaction is therefore necessary [69]. The most common plastics are now made from petrochemicals, although demand for green plastics is increasing. A more sustainable society and solutions to the world's waste management and environmental issues will result from the use of polymers derived from sustainable sources and biodegradable plastics, which break down in the environment [70].

The shift to a more sustainable circular plastics industry depends on the development of novel polymers that are effectively made from abundant carbon and appropriately formulated for end-of-life. The fabrication of intrinsically recoverable polyesters through ring-opening polymerization (ROP) of bicyclic lactones is a promising approach, many lactone compounds lack an efficient synthesis path from biobased starting materials, even though this is required to environmentally reduce material loss throughout their lifespan. Reference [71] reported the remarkably regulated and fast polymerization of a biobased γ-butyrolactone monomer (M1) coupled with tricyclic oxanorbornene. Polyester P(M1) has an excellent temperature at which glass transitions (Tg = 120 °C) were created with a low dispersity ($D = 1.2 - 1.3$) and tuneable mass up to $Mn = 76.8\ kgmol^{-1}$ [71]. Fig. 7 adapted from [71], show the monomers of multicyclic lactones for ring-opening polymerizations.

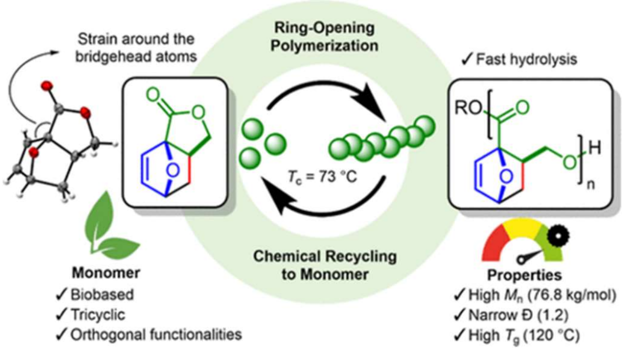

Fig. 7. Monomers of multicyclic lactones for ring-opening polymerizations. Adapted from the work of [71]. Open access 2024.

The biomaterial employed in scaffolding could likewise disintegrate if the aid is unwarranted. Natural polymers, however, might have an unfavorable immunological reaction and experience quality variations from batch to batch [52].

The applicability of conductive biodegradable polymers is hindered by their limited processability and structural fragility. Thus, electrospinning, coatings, or chemical layering via in situ polymerization should be used to create conductive polymeric composites based on conductive polymers and benign biodegradable polymers (natural or manufactured) [55]. For example, considering the potential of PANI-nanocomposite highlighted in the previous section, the production of PANI-grafted nanocomposite material is anticipated to pave the way for novel applications in the future [54].

As organic medicinal polymers, collagen, fibrin, and chitosan are commonly used because of their high adaptability, ability to support cell structures, and capacity to promote cell attachment and proliferation. However, they may also have poor mechanical strength due to their tendency to deform. The relationship between molecular mass, structure, and degradation rate of synthetic polymers such as PLA, PVA, and polycaprolactone (PCL) can be precisely controlled. Cell loss occurs due to uneven cell distribution caused by the lack of attachment points on the polymer surfaces. Improvements are needed in the polymer's mechanical properties, such as fluidity and surface roughness, before they can be used in medical implants.

The development of polymers that degrade and their combined materials, utilizing 3D printing, is hindered by several significant issues. First, it can be difficult to create suitable resources. These composites' biodegradability and the requirement for vital mechanical qualities like durability and adaptability must be carefully reconciled [6], [72-74]. Researchers must adjust variables such as temperature, speed, and layer height to ensure consistent and reliable 3D printing results. As efforts toward a more sustainable society advance, future developments are expected to focus on maintainability and the integration of artificial intelligence to enable fully closed-loop life-cycle management of additively manufactured components.

V. CONCLUSION

This review has examined the emerging landscape of renewable polymer systems for biomedical interfaces, bioadhesive technologies, and their integration with 3D printing. Collectively, the literature demonstrates that renewable polymer platforms derived from biomass, non-edible oils, and bio-based feedstocks offer a credible pathway toward reducing dependence on fossil-derived materials while enabling functional performance suitable for medical and engineering applications. Within this framework, bioadhesive systems represent a key translational bridge, supporting tissue sealing, wound closure, implant fixation, and scaffold integration, while 3D printing provides the precision and structural adaptability needed to fabricate patient-specific architectures. Despite meaningful progress, challenges remain. Mechanical limitations, wet-surface adhesion, degradation control, variability in biological response, and constraints in clinical scalability continue to limit widespread deployment. In 3D printing, printability, material stability, and regulatory compliance present additional technical and translational barriers. Addressing these gaps will require coordinated advances in polymer chemistry, processing technologies, standardization of testing protocols, and sustainable manufacturing strategies. Looking forward, the future of renewable polymer research is expected to be driven by molecular design of tunable and auto degradable polymers, hybrid bioadhesives with improved wet-surface adhesion and biomechanical compatibility, bioink development for regenerative medicine and implantable devices, and circular systems enabling recycling, closed-loop reuse, and reduced environmental burden. Overall, renewable polymers hold strong potential to redefine biomedical material design when supported by continued research, policy engagement, and responsible industrial adoption. Their successful integration into clinical and manufacturing environments may accelerate the transition toward safer, more efficient, and environmentally sustainable biomedical technologies.

DECLARATION OF COMPETING INTEREST

The authors report no known competing financial interests or personal relationships that could have influenced the work described in this paper.

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