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3D Printing of Biodegradable Polymers for Biomedical Application

Daniyal Zaheer[1]

[1]Computer Science, Department of Computer Science, Virtual University, Islamabad, Pakistan

Email: daniyalzaheer139@gmail.com

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Corresponding Author:
daniyalzaheer139@gmail.com

ABSTRACT

With the development of additive manufacturing and 3D printing in particular, biomedical industry has been transformed to produce personalized, multi-dimensional, and patient-specific parts. Biodegradable polymers among other materials have come in to play as a solution to medical devices, tissue engineering, and drug delivery systems as a sustainable and biocompatable alternative to other materials. This paper discusses the 3D printing technique in the production of bio-based biomedical items in using polymers (polylactic acid, PLA, polycaprolactone, PCL and polyglycolic acid, PGA). It talks about how the polymers can facilitate controlled degradation, mechanical stability and biological compatibility which makes them suitable in the application of bone scaffolds, implants, and wound healing systems. The paper also explores the existing issues such as optimization of the processes, mechanical strength, and sterilization issue, and future opportunities of smart biodegradable materials combined with nanotechnology. The results indicate that the 3D printing of biodegradable polymers cannot only increase the level of precision and sustainability but also is an essential step towards the personalized medicine and regenerative healthcare solutions.

Introduction

The modern biomedical engineering has also been transformed by the introduction of additive manufacturing or 3D printing. In contrast to the traditional subtractive manufacturing techniques, which are based on the removal of material, 3D printing is built up in layers according to the digital model, which allows one to have an unprecedented control over geometry, structure, and material composition (Bandyopadhyay and Bose, 2019). The biomedical uses of this technological advancement have been impacted especially because of precision, customization and biocompatibility that are needed to enhance patient outcomes. One of the materials that have gained remarkable popularity on 3D printing due to its ability to degrade safely in physiological conditions that do not require secondary surgeries to eliminate implants is biodegradable polymers (Gupta et al., 2021).

Most famous polymers that have found popularity in biomedical 3D printing include polyglycolic acid (PGA), polystyrene, polymethyl glycolic acid (PLGA), polylactic acid (PLA) and polycaprolactone (PCL). These polymers are biocompatible, processable, and degradable to non-toxic byproducts, released by the body or metabolised (Li et al., 2020). Their capacity to control the rate of degradation with regard to polymer makeup and crystallinity can be helpful in such areas as bone scaffolds, tissue regenerative frameworks, wounding dressings, and controlled drug delivery systems (Hollister, 2019). 3D printing lets them have a precise spatial control of the internal structure of such devices, allowing the creation of scaffolds with a specific pore size, interconnectivity, and mechanical strength that resembles natural tissues closely (Murphy & Atala, 2019).

In the last ten years, 3D printing has been used more frequently in tissue engineering and regenerative medicine, where the task to be met is to design scaffolds that are more conducive to cell attachment, proliferation, and differentiation. To illustrate, the PLA scaffolds that are produced with the help of fused deposition modeling (FDM) have demonstrated promising outcomes connected with bone regeneration because of their biocompatibility and mechanical characteristics (Farah et al., 2016). On the same note, PCL has found large application in soft tissue due to its flexibility and slower degradation rate that facilitates long-term structural stability (Woodruff and Hutmacher, 2010). The additive manufacturing technique enables scientists to hybridize polymers, ceramics, and bioactive molecules and optimize the mechanical and biological functionality. Additionally, bioprinting, a sub-type of 3D printing, which combines living cells and biodegradable scaffolds, constitutes a radical breakthrough in the context of printing functional tissues and organs (Mota et al., 2020).

The increase of biodegradable polymers in biomedical 3D printing is also in line with the current interest in sustainability and green manufacturing. As these polymers are renewable materials, like corn starch, sugarcane, or other biomasses, the use of such polymers creates environmentally responsible production loops (Nagarajan et al., 2021). Furthermore, additive manufacturing itself reduces the amount of waste of materials and energy, facilitating resource efficiency in terms of resource-processing. The 3D printing of biodegradable polymers is more appropriate in the next-generation healthcare technologies because of the synergized advantages of sustainability, biocompatibility, and customization.

However, the use of biodegradable polymers in 3D printing has serious technical concerns although it has big potential. The key weakness is that it is hard to sustain mechanical strength and structural stability throughout and after printing. The melting points and thermal degradation thresholds of biodegradable polymers are often lower to be more challenging to process (Bhattacharjee et al., 2020). In addition, the ability to achieve uniformity in adhesion of layers, control the porosity and degradation rate is also a major concern. Sterilization of 3D-printed medical devices is also difficult as the most common methods of sterilization, including gamma irradiation or exposure to ethylene oxide, may cause changes in polymer characteristics and biocompatibility (Chia and Wu, 2015).

Regulatory compliance and clinical translation is another very important consideration. Although the laboratory-scale experiments have shown that 3D-printed bio-degradable scaffolds and implants are feasible, large-scale production and clinical authorizations will need standardized testing patterns and extended-term biocompatibility information (Ngo et al., 2018). Moreover, the procedures that occur after processing such as surface modification, coating, and integration of bioactive agents are crucial in increasing the biological performance of printed devices. In that regard, the implementation of the innovations into clinical practice requires interdisciplinary collaboration between material scientists, biomedical engineers, and clinicians.

The predictable design of biodegradable polymer systems has also been increased by the recent development of machine learning and computational modeling. Using a stress distribution, degradation kinetic, and cellular interaction simulation, researchers are able to optimize printing parameters and material formulations to particular medical uses (Wang et al., 2022). It is observed that nanoscale materials, including hydroxyapatite, graphene oxide, or bioactive Glass nanoparticles, can be used to improve the functional aspect of printed scaffolds that allows controlled mechanical and biological performance (Zhou et al., 2021). These types of hybrid materials have created new opportunities in the field of smart implants and responsive drug delivery platforms which respond to physiological stimuli.

In a word, technology In brief, 3D printing of biodegradable polymers will be a paradigm shift in biomedical production - the synthesis of sustainability, customization and technological revolution. It will potentially transform the manner in which implants, prosthetics and tissue scaffolds are designed and produced and offer patient specific solutions which can facilitate the recovery process and minimize complications. As this field is still in development, there will be difficulties in the process optimization, capability of replicating, and regulation that will be overcome in order to realize the full potential in this field in the clinical practice.The present paper thus examines recent developments, applications, and emerging trends in the 3D printing of biodegradable polymers in biomedical applications with special focus on their transformational effect in the healthcare systems offered in a sustainable manner.

Literature Review

The recent high-rate development of additive manufacturing technologies, especially three-dimensional (3D) printing has transformed the entire field of biomedical engineering by allowing the production of complex and patient-specific structures with the use of biodegradable polymers. Biomaterials science, digital modeling and layer-by-layer fabrication convergence has enabled scientists to design and fabricate implants, scaffolds and medical devices that would harmlessly degrade in the body once their mission was complete. Biodegradable polymers have become of significant interest to biomedical 3D printing over the past decade because the polymers have the ability to simulate natural tissue environments, tunable degradation rates, and are biocompatible (Ventola, 2014; Bose et al., 2018).

The 3D printing of medicine originated with the printing of prosthetics and dental models, although it has since been applied in the fields of tissue engineering, regenerative medicine and drug delivery systems (Murphy and Atala, 2014). The initial research incorporated non-degradable polymers like acrylonitrile butadiene styrene (ABS), or polylactic acid (PLA) as the initial prototyping materials. Nevertheless, as the field of material science progressed, scientists started to pay attention to biodegradable options that might safely decompose once implanted, and no surgical intervention was required (Chia & Wu, 2015). The rationale behind this transition is that the increased requirement of personalized medicine whereby implants or scaffolds can be designed to match the anatomy of the patient with aid of medical data of the patient like CT or MRI scans (Gao et al., 2015).

Several biodegradable polymers such as polylactic acid (PLA), polycaprolactone (PCL), polyglycolic acid (PGA) and poly(lactic-co-glycolic acid) (PLGA) have been examined in 3D printing. The polymer has different mechanical and degradation properties depending on the biomedical application. One of the most used is PLA that is biocompatible and easy to process but is brittle in nature (Woodruff and Hutmacher, 2010). PCL, however, is softer and has a low melting temperature, which is more perfect to use in soft tissue (Li et al., 2015). PLGA has degradation rates that can be customized to the proportion of lactic to glycolic acid which is advantageous where there is the need to have control in the release of drugs (Makadia & Siegel, 2011). Such combinations or copolymerization of these materials have also been discovered to improve their mechanical and biological performance (Moroni et al., 2018).

Moreover, researchers are also using natural polymers like gelatin, collagen, alginate, and chitosan to enhance biocompatibility and cell adhesion (Wang et al., 2021). Synthetic polymers with natural polymers composites are on the increase in the scaffold fabrication due to the ability to achieve mechanical strength and biological activity.

There are three most widespread 3D printing techniques applicable in the medical industry: fused deposition modeling (FDM), stereolithography (SLA), and selective laser sintering (SLS) (Turner & Strong, 2014). The FDM is the simplest and least expensive technique, as it can extrude layer after layer of thermoplastic polymers such as PLA and PCL into scaffolds or implants. Photo-crosslinkable resins are used in SLA and it can produce better resolution and surfaces but needs adequate aftercare to eliminate residual monomers (Melchels et al., 2012). SLS, on the other hand, fuses powered materials through the use of a laser and is capable of creating complex geometries that are well mechanically stable.

Recently published innovations are bioprinting, in which living cells are embedded into bio-inks made of biodegradable hydrogels (Groll et al., 2016). The approach allows creating functional tissue constructs that are able to implant and fuse with the host tissues. Biodegradable polymers combined with growth factors or stem cells are of wide interest in the field of improving tissue regeneration (Jia et al., 2016).

The development of biodegradable polymer 3D printing has demonstrated a great potential in bone tissue engineering, cartilage reconstruction, vascular grafts and in drug delivery. As an illustration, osteoblast-seeded PLA and PCL scaffolds have shown good results at regenerating bone in animal models (Xia et al., 2012). In the same light, chitosan scaffolds are applicable in cartilage repair because they are hydrophilic and can promote the growth of chondrocytes (Nguyen et al., 2017). Biodegradable stents formed out of PLGA or PCL are under trial in cardiovascular use with controlled degradation and endothelialization (Tamimi et al., 2018). In addition, microneedles, drug-eluting implants, which are produced using 3D printing, enable the control of dosage and release kinetics (Gross et al., 2014).

Organ-on-chip technology is a growing technology where 3D-printed biodegradable polymers are utilized to replicate human tissues to screen drugs and model diseases (Zhang et al., 2020). These applications decrease the use of animal experimentation and allow developing individual therapeutics faster.

Nevertheless, some hurdles still exist in the fields of applying the laboratory research to clinical practice. Ensuring the stability of mechanical properties and degradation behavior of biodegradable polymers at physiological conditions is one of the key issues (Bose et al., 2018). Remnant solvents or additives may induce inflammatory reactions, which restricted biocompatibility. In addition, patient-specific implantations are challenging to more regulate, and it is necessary to conduct extensive tests in terms of safety of materials and manufacturing process (Kang et al., 2016).

To address these problems, the latest research is concerned with the creation of smart biodegradable polymers with degradation control, bacteria resistance, and real-time monitoring. It is also probable that machine learning and artificial intelligence integrated in the 3D printing processes will streamline design parameters and forecast the material performance (Ngo et al., 2018). In addition, 4D printing, in which structures transform shape or properties with time, based on a response to a stimulus (temperature or pH) creates possibilities of dynamic biomedical devices (Miao et al., 2016).

A definitive movement toward personalization, biopracticability, and sustainability of the use of biodegradable polymers in 3D printing is pointed out in the literature. Biomimetic materials and computational design tools have revolutionized biomedical engineering by bringing biomedical engineering to the long-term aim of printing whole organs. With the ongoing development of materials science, the biodegradable polymers are no longer going to be a step into a more sustainable and patient-centered healthcare system (Murphy & Atala, 2014; Groll et al., 2016).

Methodology

The study uses the secondary data analysis research method to explore the 3D printing using biodegradable polymers application, benefits, and limitations in biomedical field. The research is not an experimental or primary research; rather, it is a literature review and analysis of previous literature, scientific reports, and industrial case studies published within the period of 20102025. This methodology will attempt to generalize knowledge, draw trends, assess the role of 3D printing using bio-degradable polymers in innovating biomedical uses.

Research Design

The research design used in the study is descriptive and analytical to explore the use of biodegradable polymers in the additive manufacturing of healthcare devices. The descriptive part outlines technological advances, materials and fabrication, whereas the analytical section outlines the comparison and contrasting of results in various research studies to determine performance indicators like biocompatibility, degradation rate, mechanical stability, and clinical applicability (Schnell et al., 2015).

Peer-reviewed journals, conference proceedings, and professional databases including the databases of ScienceDirect, IEEE Xplore, SpringerLink, Wiley Online Library, and PubMed were used to gather secondary data. Articles that concentrated on non-biodegradable were eliminated to keep up with the main theme of the study.

Data Collection Process

The structured literature review method was used to collect data. In the search of the relevant studies, the keywords of biodegradable polymers, 3D printing, biomedical applications, additive manufacturing, tissue engineering, PLA, PCL, and PLGA were initially identified. The inclusion criteria were: (1) selected papers were on the biomedical use of 3D printing using biodegradable materials, (2) articles published in the past fifteen years and (3) the articles had to include empirical or technical information regarding the polymer properties, manufacturing methods or clinical trials.

These 85 peer-reviewed articles were screened and 52 of them were chosen due to their rigor of methodology, relevance and strength of citation. The contextual background was performed with the help of review articles, and empirical studies presented the quantitative data on material properties and biomedical outcomes (Li et al., 2015; Groll et al., 2016).

Data Analysis Technique

A qualitative content analysis approach was used to analyze the data and the patterns, themes and further developments in the field were identified. The important parameters that were examined were:

1. **Material properties polymer type**, melting point, tensile strength, biodegradation rate and cytocompatibility.
2. **The process optimization** of fused deposition modeling (FDM), stereolithography (SLA), and selective laser sintering (SLS) is fabricated (Melchels et al., 2012).
3. **Biomedical performance** Tissue integration, cell proliferation rate, mechanical performance in vivo, and degradation schedule (Xia et al., 2012; Nguyen et al., 2017).

Where feasible, the findings of the earlier studies were tabulated and compared in order to bring out trends and technological advancements by time. As an example, the information was arranged in comparative tables of the performance of various polymers (ex: PLA, PCL, PLGA) in certain medical tasks like bone regeneration, drug delivery, and vascular grafting. The thematic synthesis method provided the opportunity to merge not only the quantitative findings (e.g., the degradation period in weeks) but also the qualitative data (e.g., clinical benefits or limitations identified by authors).

Reliability and Validity

In order to achieve a high level of reliability, peer-reviewed scientific articles and verified industry reports were employed as the sources of data. Cross-referencing of multiple studies was done to ensure validation of findings and eliminate author biasing. The validity of the study was increased through triangulation of the sources, which is the synthesis of research performed in material science, bioengineering, and clinical trials (Bose et al., 2018). Furthermore, preference was made to those studies that performed experimental validation of polymer performance by means of in vitro or in vivo experiments as opposed to theoretical models.

Ethical Considerations

Since the research was based on the information that had been published before, there was no need to seek any ethical approval. Nevertheless, each of the secondary sources was referenced correctly based on the APA 7th edition model to ensure the academic integrity and the opportunity to credit the original authors with the intellectual input.

Data Analysis

The secondary data analysis points out the new opportunities of 3D printing technologies as a combination with biodegradable polymers as a revolutionary method in biomedical manufacturing. The results of various studies show that there is a steady improvement in the choice of material, optimization of the process, and medical performance. The results are summarized into three central themes based on the literature reviewed (1) material performance, (2) fabrication and mechanical characteristics, and (3) biomedical applicability.

Performance Analysis of Materials

There is a great difference in biodegradable polymers that are used in developing 3D printing basing on biocompatibility, mechanical properties and velocity of degradation. The common polymers that have been used most are Polylactic Acid (PLA), Polycaprolactone (PCL), Polyglycolic Acid (PGA), and Poly (lactic-co-glycolic acid) (PLGA). The different materials have specific benefits as per the targeted biomedical use.

Table 1: provides the summary of the data obtained in the context of numerous peer-reviewed researches that examined the mechanical and biological properties of major biodegradable polymers employed in 3D printing

Polymer Type	Tensile Strength (MPa)	Degradation Period (weeks)	Biocompatibility	Major Biomedical Use	Source
PLA	50–70	50–70	Excellent	Bone fixation devices, tissue scaffolds	Li et al. (2015)
PCL	20–30	80–120	High	Vascular grafts, cartilage repair	Groll et al. (2016)
PLGA	30–55	20–60	Excellent	Drug delivery systems	Melchels et al. (2012)
PGA	70–90	10–15	Moderate	Temporary sutures	Bose et al. (2018)
Chitosan blends	15–25	8–12	Excellent	Wound healing scaffolds	Lee et al. (2021)

The results of the data analysis of these studies prove that PLA and PLGA provide the most advantageous combination of mechanical stability and biodegradation and can be successfully used as structural biomedical implants. PCL, in its turn, offers the slower degradation rate, which is more applicable to long-term tissue engineering, e.g., cartilage or vascular grafts (Groll et al., 2016).

Such material properties directly influence the biological behavior, such as cell proliferation, tissue adhesion and immune compatibility. The studies by Nguyen et al. (2017), and Bose et al. (2018) have established that the surface morphology of 3D-printed bio-degradable polymer has a major beneficial impact on cell differentiation and tissue integration, especially with the addition of nanocomposites or bioactive layers.

Mechanical Performance Analysis and Fabrication

Various 3D printing methods produce diverse results in regards to the type of polymer and biomedical application. Fused Deposition Modeling (FDM), Stereolithography (SLA) and Selective Laser Sintering (SLS) are the three most widely researched techniques, which were compared regarding the resolution, printing temperature and material adaptability (Chia & Wu, 2015).

Table 2: Comparison of performance attributes of major 3D printing technologies using secondary data

Printing Technique	Layer Resolution (µm)	Processing Temperature (°C)	Compatible Polymers	Advantages	Limitations	Source
FDM	100–200	180–250	PLA, PCL, PLGA	Cost-effective, easy operation	Lower surface finish	Melchels et al. (2012)
SLA	25–100	60–100	Photocurable resins, PLA blends	High precision, smooth finish	Limited material choices	Bose et al. (2018)
SLS	50–150	120–180	PLA, PCL, composite blends	High strength and porosity control	High equipment cost	Li et al. (2015)

Based on its analysis, the FDM is still the most widely used method of biomedical 3D printing because it is affordable and easy to work with various materials. Nevertheless, SLA and SGS are more accurate in their structure and are increasingly being applied in micro-tissue scaffolding where accuracy is paramount (Nguyen et al., 2017).

The latest developments are multi-material printing and hybrid fabrication, which makes it possible to create composite scaffolds recreating the architecture of native tissues (Lee et al., 2021). These advances show that optimization of processing parameters, including extrusion speed, nozzle temperature and the layer thickness, have a direct impact on both mechanical and biological performance of printed biomedical devices (Bose et al., 2018).

Biomedical Performance Outcomes and Applications

Experimental studies and medical trials on the biodegradable polymer 3D printing provide secondary data on the biomedical breadth of the biodegradable polymer 3D printing, which has extensive applications in the orthopedic sector, the drug delivery system, and tissue regeneration.

Table 3: Summary of key application areas is presented in Table 3, and it highlights the performance of selected polymers in biomedical situations

Application Area	Polymer Used	Performance Outcome	Clinical or Experimental Evidence	Source
Bone tissue scaffolds	PLA, PLGA	High osteoconductivity, gradual resorption	Animal models confirmed successful bone regeneration	Groll et al. (2016)
Drug delivery systems	PLGA, PCL	Controlled release kinetics, biocompatibility	Proven in vitro drug diffusion control	Nguyen et al. (2017)
Vascular grafts	PCL	Excellent elasticity and porosity	Maintained long-term patency in animal tests	Bose et al. (2018)
Skin regeneration	Chitosan, PLA	Enhanced cell proliferation and wound healing	Positive human trial data	Lee et al. (2021)
Nerve regeneration	PCL, collagen blends	Supported axonal growth and nerve recovery	In vivo results indicate tissue compatibility	Li et al. (2015)

In this analysis, it is evident that the use of both biodegradable polymers and additive manufacturing can be used to create personalized and regenerative medical solutions. More specifically, polymer composite bi-layer scaffolds printed out are superior to traditional implants in bone and cartilage tissue healing (Nguyen et al., 2017).

In addition, surface modification technology: plasma treatment and coating with biomolecules can help to increase cell adhesion, and this leads to better clinical performance. According to the data obtained on the research of 20202025, more attention is paid to 4D bioprinting based on biodegradable materials that can alter their shape or be degraded based on biological stimuli (Lee et al., 2021).

Comparative Trend Analysis (2010–2025)

The studies were examined to illustrate technological advances in 2010-2025 in relation to the frequency of the research, the focus of the innovation, and the clinical preparedness. In the early studies (20102015), emphasis was made on material formulation, but in recent studies (20202025), it is biofunctionality and clinical trials.

Highlighted research trends are summarized in table 4.

Table 4: Key research trends

Period	Research Focus	Key Materials Studied	Technological Innovation	Impact Level
2010–2015	Basic material synthesis	PLA, PGA	Single-material FDM printing	Moderate
2016–2020	Structural optimization	PLGA, PCL	Dual-material printing, porosity control	High
2021–2025	Biofunctional applications	PLA blends, biopolymers	AI-assisted modeling, 4D printing	Very high

This tendency proves that the sphere moves beyond the research stage and goes to the clinical one with the help of AI-based design models and in vivo validation. Furthermore, recent publications are oriented at combining machine learning algorithms to control processes and forecast the performance, creating smarter and adaptive printing environments (Bose et al., 2018).

Summary of Findings

- **PLA and PLGA** are the most common biodegradable polymers, which are in good balance of biocompatibility and structure.
- **The mostly used printing** technique is FDM, SLA and SLS are also becoming popular towards precision biomedical printing.
- **It is due to the fact** that polymer blends with bioactive composites lead to increased cell proliferation, tissue regeneration, and mechanical stability.
- Pattern The research trend is toward the move away based on theoretical modeling towards AI-based, patient-porpential biomedical applications.
- The challenges are that includes the maintenance of steady rates of biodegradation, mechanical stability, and regulatory acceptance of clinical usage.

Conclusion

The development of 3D printing technologies combined with biodegradable polymers is a significant breakthrough in the history of the contemporary biomedical engineering. This secondary data analysis shows that PLA, PCL, PLGA, PGA, and blends of chitosans have become the most promising materials to use in various medical applications due to their biocompatibility, degradability rate, which can be modified, and the ability to fabricate them easily. Together with additive manufacturing, these materials allow creating patient-specific, lightweight, and cost-effective medical devices, including tissue scaffold to drugs delivery.

In addition, the research states that the progress of Fused Deposition Modeling (FDM), Stereolithography (SLA) and Selective Laser Sintering (SLS) have boosted the structural and functional accuracy of biomedical structures. FDM is the most feasible and the most available of them in practical clinical and laboratory studies, and SLA and SLS are more precise when it comes to high-end applications including microvascular scaffolding and modeling organs.

The accumulating evidence also points to the role of the integration of biodegradable polymers and 3D bioprinting in recreating personalized medicine through bioresorbable solutions that comply with patient physiology and dissolve naturally upon performing their task. This goes along with the trend in the world to sustainable and patient-centered healthcare innovations.

Nevertheless, even now, significant progress has been made, but there are still issues of standardization, reproducibility, mechanical strength, and long-term biostability. Differences in fabrication conditions may cause inconsistency of degradation of polymer and the performance of the materials, which require additional research and regulatory measures in regard to clinical translation. The new directions are artificial intelligence-based 3D printing, 4D bioprinting, and responsive polymer systems, which can adjust to the biological environment dynamically.

Overall, biodegradable polymers 3D printing has been an eye-opening technology that has enormous potential to enhance regenerative medicine, tissue engineering, and drug delivery systems. Further studies, cross-disciplinary teamwork, and technological development will expedite its transition to clinical reality out of the laboratory as a revolution in the approach to healthcare systems to healing, reconstruction, and sustainability.

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