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"Polycaprolactone (PCL)" - A New Material with Long Journey in Dentistry-A Review

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ABSTRACT: Because of its advantageous mechanical and biological characteristics, polycaprolactone (PCL), a biodegradable, biocompatible, and adaptable polymer, has drawn more and more interest in dental applications. PCL is mostly utilized in regenerative dentistry, which includes scaffold construction, tissue engineering, and guided tissue regeneration (GTR). It is perfect for use in periodontal and endodontic treatments because of its slow rate of disintegration, which permits sustained therapeutic effects. Furthermore, PCL is being investigated as a base material for 3D printing dental prosthetics and custom restorations, offering great design and production freedom. Although PCL exhibits encouraging biocompatibility and customization outcomes, its use in load-bearing applications, such as permanent dental prostheses, is limited by its inferior mechanical strength when compared to more traditional materials like PMMA (polymethyl methacrylate). According to recent research, PCL composites, like PCL-HA (hydroxyapatite), have the potential to improve bone regeneration and osseointegration in periodontal therapy and implantology. The current status of PCL research in dentistry is reviewed, along with its uses, benefits, and drawbacks when compared to conventional dental materials.

KEYWORDS: Polycaprolactone, Dentistry, Biocompatibility, Tissue Engineering, 3D Printing, Regenerative Medicine.

I. INTRODUCTION

The polyester polycaprolactone (PCL) has a low melting point, usually around 60°C, and is biodegradable and biocompatible. Because it is semi-crystalline, it has great flexibility and durability. PCL has several uses in a variety of industries, including as engineering, dentistry, and medical, because of its special qualities. [1]

Polycaprolactone's (PCL) characteristics include: [2,3]
Biodegradability: As a result of the hydrolysis of its ester linkages, PCL gradually breaks down naturally in the environment and in the body.
It is safe to employ in biomedical applications due to its biocompatibility.
Flexibility: It is robust and flexible because to its semi-crystalline structure.
Processing Ease: PCL is readily moldable and amenable to methods such as extrusion, injection molding, and 3D printing.
Low Melting Point: It is perfect for applications needing minimal thermal deterioration at about 60°C.

PCL applications include:
1. Medical Applications: Tissue Engineering: Because PCL promotes cell growth, it is utilized to build scaffolds for the regeneration of skin, cartilage, and bones.
Drug Delivery Systems: It is used to produce biodegradable capsules and implants for drug delivery.
Because of its mechanical strength and gradual decay, orthopedics uses bone grafts and anchoring devices.
Sutures: PCL-based biodegradable sutures are frequently utilized.

2. Dental Applications: Bone Grafts and Membranes: PCL is used in implantology and periodontics for directed tissue regeneration and bone repair techniques.
3D Printed Dental Models: Because of its ability to work with 3D printing, it may be used to create dental appliances and models.
Temporary prosthodontic components: Because of their removability and ease of shape.

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3. Industrial Uses: 3D Printing and Prototyping: This material is used as a filament in additive manufacturing to create both prototypes and final products.
Hot Melt Adhesives: Because PCL is thermoplastic, it can be found in some adhesives.
Packaging: As an environmentally friendly substitute for conventional packaging materials.

4. Education Applications:
Moldable Plastic: Because of its low melting point, PCL, also known as "instamorph" or "friendly plastic," is frequently used in crafts and do-it-yourself projects.

Polycaprolactone material's Properties:
Polycaprolactone (PCL) Chemical Structure:
An artificial aliphatic polyester is polycaprolactone. Repeating units formed from ε-caprolactone, which is subjected to ring-opening polymerization to form PCL, make up its chemical structure. Here is a thorough explanation:

1. Chemical Formula:
Monomer Unit: ε-Caprolactone has the formula $C_6H_{10}O_2$.
Polymer Structure: Polycaprolactone is represented as $(C_6H_{10}O_2)_n$, where n is the degree of polymerization.

2.Chemical Structure of Polycaprolactone (PCL):
Polycaprolactone is a **synthetic aliphatic polyester**. Its chemical structure is composed of repeating units derived from ε-caprolactone, which undergoes ring-opening polymerization to form PCL.

3. Polymerization Process:
PCL is synthesized via **ring-opening polymerization** of ε-caprolactone. This is typically catalyzed by compounds like stannous octoate ($Sn(Oct)_2$).
The reaction mechanism:
1. **Initiator (alcohol)** attacks the carbonyl group of ε-caprolactone.
2. The ring opens, and successive addition of monomers occurs.
3. The chain propagates, resulting in a long polyester chain.

Physical and Mechanical Properties of Polycaprolactone (PCL)
Polycaprolactone (PCL) exhibits a range of properties that make it suitable for diverse applications. Its physical and mechanical characteristics stem from its semi-crystalline nature, aliphatic structure, and low glass transition temperature. [4,5]

1. Physical Properties [6]

Density	~1.1 g/cm³
Melting Temperature (Tm)	~58–64°C
Glass Transition Temperature (Tg)	~ -60°C (extremely flexible at room temperature)
Crystallinity	Semi-crystalline (~40-60%)
Solubility	Soluble in organic solvents like chloroform and benzene. Insoluble in water.
Degradation	Biodegrades via hydrolysis of ester bonds, typically over months to years in physiological conditions
Hydrophilicity	Hydrophobic but can be blended with other materials to modify surface properties.

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2. Mechanical Properties [7]

Tensile Strength	10–40 MPa (depends on crystallinity and molecular weight)
Elongation at Break	300–500% (highly ductile and elastic)
Elastic Modulus	300–500 MPa
Flexibility	Excellent; remains flexible at low temperatures due to low Tg.
Impact Resistance	High impact resistance because of its ductile nature.
Hardness	Soft and pliable at room temperature.

3. Thermal Properties [8]
Thermal Stability: Degrades thermally above 250°C.
Thermal Conductivity: Low, similar to other plastics.
Processing Range: Can be processed at temperatures between 70°C and 120°C, making it suitable for 3D printing, injection molding, and extrusion.

Applications of Polycaprolactone (PCL) in the Medical Field :
The literature is supporting that, there is a wide range of established applications of PCL in the medical field, such as in Tissue Engineering, 3D Bioprinting, Drug Delivery, Wound healing and Skin Regeneration, Regenerative Medicine Scaffolds, Bone Grafts and Fixation Devices, Vascular Grafts, Biodegradable Sutures, Stents and Catheters, Nerve Regeneration [9-12]

Applications of Polycaprolactone (PCL) in Dentistry
Because of its mechanical qualities that are appropriate for dental and craniofacial applications, as well as its biodegradability and biocompatibility, polycaprolactone (PCL) is being used in dental applications more and more. Its applications in dentistry include drug delivery devices, dental implants, and directed bone and tissue regeneration.

1. GTR/GBR, or guided tissue and bone regeneration
Uses: [13]
Barrier Membranes: Guided tissue regeneration (GTR) and guided bone regeneration (GBR) bioresorbable membranes employ PCL.
Function: Provides a physical barrier that stops epithelial cells from migrating into bone defects, promoting bone regeneration.
Improvements: Bioactive substances like as growth factors (e.g., BMP-2) can be placed onto membranes.
Benefits: Biodegradability removes the requirement for a second operation to remove the membrane.
Its strength and flexibility make it perfect for contouring over uneven flaws.

2. Bone Grafts and Scaffolds for Craniofacial Reconstruction
Applications: [12]
Bone Grafts:
PCL-based scaffolds are utilized in bone grafts for peri-implant deficiencies, sinus lift operations, and alveolar ridge augmentation.
3D-printed Scaffolds: Tailored scaffolds improve osteointegration and offer a perfect fit.
Combination with Other Materials: To increase osteoconductive, PCL is frequently mixed with hydroxyapatite (HA) or β-tricalcium phosphate (β-TCP)

3. Dental Implants and Prosthodontics
Applications: [14,15]
Customized Implant Coatings: To increase soft tissue adhesion and biocompatibility, PCL is applied as a coating material to titanium dental implants.
Drug-Eluting Coatings: To avoid peri-implantitis, antibiotics or anti-inflammatory medications can be added to the PCL layer.

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Temporary Prosthetics: PCL can be used to create temporary crowns and bridges because of its low melting point and ease of molding.

4. Drug Delivery in Dentistry
Applications:[16]
Periodontal Therapy: PCL microspheres are used to treat periodontitis by releasing antimicrobial drugs (such as metronidazole or chlorhexidine) under regulated conditions.
Post-Surgical Applications: Following oral procedures, PCL-based implants or films release medications including anti-inflammatory or anti-resorbtive chemicals.

5. Orthodontics
Applications: Clear Aligners and Retainers: Because PCL is flexible and long-lasting, it is combined with other polymers to create orthodontic equipment.
Anchorage Devices: By using biodegradable PCL scaffolds, orthodontic devices can be anchored without requiring hardware removal. [15]

6. Wound Healing in Oral Surgery Applications: To cover wounds and encourage healing, PCL membranes or films are used in flap surgeries and post-extraction sockets.

7. Dental Applications of 3D Printing
Applications: 3D-printed dental models, including as surgical guides and specially made scaffolds for intricate dental reconstructions, frequently employ PCL. It is perfect for additive manufacturing processes because of its low melting point and compatibility with bioinks. [17]

Advantages of PCL in Dentistry:
Biodegradable and biocompatible.
Long-term stability during tissue regeneration. Customizable properties when combined with other materials. Easy processing for 3D printing and fabrication.

Biocompatibility of Polycaprolactone (PCL) in Dentistry
Excellent biocompatibility is a well-known characteristic of polycaprolactone (PCL), which is essential for its use in dentistry. It is a dependable substance for a range of dental applications since it interacts well with biological tissues, promotes cell adhesion and proliferation, and shows no immunological reaction.

Important PCL Biocompatibility Factors [14]
1. Reaction of Cells
PCL has strong cell adhesion and proliferation, especially for osteoblasts, periodontal ligament cells, and human mesenchymal stem cells (hMSCs).
Its compatibility with tooth tissues is further improved by surface changes, such as the inclusion of hydroxyapatite or bioactive compounds.

2. Inflammatory Response [18]
PCL exhibits low immunogenicity and does not elicit a significant inflammatory reaction when implanted in vivo.
Its slow degradation minimizes acidic by-products, reducing the risk of inflammatory responses compared to other biodegradable polymers like polyglycolic acid (PGA).

3. Osteoconductivity
PCL's ability to support bone cell attachment and proliferation makes it highly suitable for dental bone regeneration, implantology, and guided bone regeneration (GBR).
When combined with osteoconductive materials like β-tricalcium phosphate (β-TCP), it enhances the bone regeneration process. [19]

4. Periodontal Tissue Compatibility
PCL membranes and scaffolds used in guided tissue regeneration (GTR) exhibit high compatibility with gingival and periodontal ligament fibroblasts, promoting soft tissue healing. [20]

5. Antibacterial Modifications
PCL's surface can be functionalized with antimicrobial agents like silver nanoparticles or chlorhexidine, enhancing its antibacterial properties without compromising biocompatibility. This is particularly beneficial in preventing infections in periodontal and peri-implant surgeries. [21]

6. Long-Term Biodegradability
PCL degrades slowly (over months to years), providing long-term support for tissue regeneration in dental applications. Its degradation products (caproic acid) are non-toxic and easily metabolized by the body. [7]

Polycaprolactone (PCL) and Osseointegration
Osteointegration, or the direct structural and functional bond between living bone and the surface of a load-bearing artificial implant, is supported by polycaprolactone (PCL). Although PCL is naturally biocompatible, material modifications frequently increase its osteoconductive, which makes it a great option for dental implant-related applications and bone regeneration.

Important Elements That Promote Osseointegration
1. Cell Adhesion and Biocompatibility
Osteoblast adhesion, proliferation, and differentiation are all facilitated by PCL.
By imitating the extracellular matrix (ECM), PCL scaffolds can stimulate the cellular reactions required for osseointegration. [22]

2. Osteoconductivity
Although pure PCL is not osteoconductive by nature, it promotes osseointegration when mixed with bioactive substances such as
Hydroxyapatite (HA): Enhances mineralization and osteoblast adhesion.
Bone formation is stimulated by β-Tricalcium Phosphate (β-TCP), which increases the release of calcium ions.
Graphene Oxide (GO): Boosts bioactivity and mechanical strength. [14]

3. Scaffold Design and Surface Topography
Porosity: PCL scaffolds are engineered with interconnected pores to facilitate vascularization, bone in-growth, and nutrient exchange.
3D Printing: Customized 3D-printed PCL scaffolds provide patient-specific implants, improving the fit and integration into native bone. [23]

4. Controlled Degradation
PCL's slow degradation rate allows sufficient time for bone remodeling and integration, ensuring the scaffold maintains mechanical support during osseointegration. [7]

5. Drug Delivery for Enhanced Integration
PCL can serve as a carrier for growth factors like bone morphogenetic proteins (BMPs) or vascular endothelial growth factors (VEGF). These factors accelerate osteogenesis and angiogenesis, further supporting osseointegration. [24]

Clinical Applications Demonstrating Osseointegration
Dental Implants:
PCL coatings on titanium implants improve surface bioactivity and promote better integration with surrounding bone.
Bone Grafts and GBR:
PCL-HA membranes are used in guided bone regeneration (GBR) to support osseointegration in peri-implant defects.
Craniofacial Reconstruction:

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PCL scaffolds are employed in alveolar ridge augmentation and sinus lift procedures, providing a conducive environment for bone in-growth.
Experimental Evidence
Study 1: PCL-HA Composites
Researchers demonstrated that PCL-Hydroxyapatite scaffolds significantly enhanced bone regeneration and osseointegration compared to pure PCL scaffolds.[14]
Study 2: PCL-β-TCP Scaffolds in Dental Applications
PCL-β-TCP scaffolds showed robust bone formation and osseointegration in craniofacial defect models. [19]

Role of Polycaprolactone (PCL) in Prosthodontics
Because it is moldable, biocompatible, and compatible with new technologies like 3D printing, polycaprolactone (PCL) is used extensively in prosthodontics. Dental implants, soft and hard tissue prosthesis, and medication delivery systems specifically designed for prosthodontic treatment are some of its uses.

Prosthodontic Applications of PCL
1. Personalized Scaffolds for the Regeneration of Bone and Soft Tissue
Application: PCL is utilized in scaffolds to promote bone and soft tissue regeneration, particularly when jawbone abnormalities make prosthodontic procedures like implant insertion more difficult.
For instance, alveolar ridge augmentation uses scaffolds based on PCL to restore bone volume so that implants or dentures fit properly.
Improvements: To encourage osteogenesis, PCL scaffolds can be mixed with bioactive substances like hydroxyapatite or β-tricalcium phosphate (β-TCP). [22]

2. Denture Base Materials
Application: PCL is utilized in flexible and durable denture bases, providing comfort and adaptability for edentulous patients.
Its low melting point enables ease of customization and relining.
PCL-based thermoplastic materials are ideal for partial dentures due to their flexibility and biocompatibility. [25]

3. Implant Coatings
Application: PCL serves as a bioactive coating for dental implants to enhance osseointegration and reduce the risk of implant failure.
Drug-Eluting Coatings: Incorporation of antimicrobial or anti-inflammatory agents in PCL coatings helps prevent peri-implantitis. [10]

4. Temporary Prosthetics
Application: PCL's moldability makes it an ideal material for fabricating temporary crowns, bridges, and partial dentures during interim periods.
Advantage: Customizable fit and ease of removal with heat application.

5. 3D Printing for Custom Prostheses
Application: PCL is widely used in 3D-printed dental models and custom prosthetic devices.
Example: Fabrication of patient-specific craniofacial prostheses, such as maxillofacial obturators.
Advantage: Enables precise fit and reduced chairside time for adjustments. [23]

6. Drug Delivery Systems in Prosthodontics
Application: PCL-based drug delivery systems are integrated into prosthetic devices to release antibiotics or analgesics post-surgery.
Example: PCL films or microspheres incorporated into denture liners to deliver antifungal agents in cases of denture stomatitis. [16]

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Advantages of Using PCL in Prosthodontics [15]

Biocompatibility: The likelihood of negative reactions is reduced because PCL is well-tolerated by oral tissues.
Personalization:
Because it is thermoplastic and has a low melting point, prostheses can be easily molded, adjusted, and customized.
Durability: PCL is appropriate for stress-bearing applications due of its exceptional mechanical qualities, which include great flexibility and long-term stability.
Improved Regeneration: PCL scaffolds facilitate angiogenesis and osteoconduction, which speeds up healing and prosthetic device integration.
Manufacturing Ease: PCL makes it easier to create precise, patient-specific prostheses by being compatible with additive manufacturing procedures.
Cost-Effectiveness: PCL is a cost-effective option for prosthodontic applications because it is comparatively cheap when compared to other biopolymers.

Challenges and Solutions
gradual deterioration: In situations that recover quickly, PCL's gradual deterioration may be a drawback.
Solution: To adjust degradation rates, blend with polylactic acid (PLA), a polymer that breaks down more quickly.
Osteoconductivity: Pure PCL is not naturally osteoconductive.
Solution: Adding growth hormones or bioactive fillers (such HA or β-TCP) to promote bone repair.
In prosthodontics, polycaprolactone has become a versatile material that addresses important issues with implant success, denture construction, and bone regeneration. It is a useful material in current prosthodontics because of its versatility, biocompatibility, and compatibility with cutting-edge fabrication methods like 3D printing.

Role of Polycaprolactone (PCL) in Other Dental Specialties
Polycaprolactone (PCL) has gained significant attention across various dental specialties due to its biocompatibility, biodegradability, and ability to be combined with other materials for enhanced properties. Its versatility makes it applicable in specialties like periodontics, endodontics, orthodontics, pediatric dentistry, and oral surgery.

1. Periodontics
Applications: Guided Tissue Regeneration (GTR): GTR uses PCL to create membranes that allow periodontal tissues to grow again. These membranes foster the healing of bone and periodontal ligaments by preventing the migration of epithelial cells.
For instance, PCL-HA membranes promote the regeneration of periodontal tissue and osteoblast activity.
Systems for Drug Delivery:
To treat periodontitis and encourage healing, PCL-based scaffolds or films that are laden with antibiotics or anti-inflammatory drugs are utilized. [20]

2. Endodontics
Applications:
Root Canal Filling Material:
PCL is used as a biodegradable component in root canal filling systems, particularly in bioactive composites designed for apexification or root regeneration.
Regenerative Endodontics:
PCL scaffolds provide a platform for cell proliferation and differentiation, facilitating the regeneration of the dental pulp and periapical tissues. [26]

3. Orthodontics
Applications:
Sustained Drug Delivery Systems:
PCL-based systems are used to deliver fluoride or antibacterial agents in orthodontic adhesives to prevent enamel demineralization around brackets.
Temporary Anchorage Devices (TADs):

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PCL coatings on orthodontic mini-implants enhance biocompatibility and osseointegration, reducing the risk of implant failure. [27]

4. Pediatric Dentistry
Applications:
Scaffolds for Regenerative Dentistry:
In pediatric patients with immature teeth, PCL scaffolds support the regeneration of dental pulp and root structures.
Space Maintainers:
PCL-based thermoplastics are used for customized, flexible space maintainers due to their moldability and biocompatibility. [28]

5. Oral and Maxillofacial Surgery
Applications:
Bone Regeneration:
PCL is extensively used in oral surgery for guided bone regeneration (GBR), especially in cases of alveolar ridge augmentation, sinus lifts, and mandibular defects.
Example: PCL-β-TCP scaffolds support bone growth and vascularization in large craniofacial defects.
3D-Printed Surgical Models:
PCL is utilized for creating patient-specific surgical guides and models for complex maxillofacial procedures. [19]

6. Implantology
Applications:
Implant Coatings:
PCL is used as a bioactive coating for dental implants, promoting osseointegration and reducing peri-implantitis.
Advantage: Can be loaded with growth factors or antimicrobial agents for enhanced functionality.
Bone Substitute Materials:
PCL-based composites (e.g., PCL-HA) are used as bone graft substitutes to fill peri-implant defects. [15,18]

II. CONCLUSION

the function of polycaprolactone (PCL) in dentistry, it is critical to highlight its increasing importance because of its special qualities, which include biodegradability, biocompatibility, and adaptability. Tissue engineering, regenerative dentistry, and the creation of personalized prosthetics are three areas where PCL has found significant use. It is especially helpful in applications like guided tissue regeneration (GTR) and dental pulp regeneration because of its capacity to encourage cell adhesion and enhance tissue regeneration.

But even though PCL has a lot of promise, its usage in some load-bearing applications is limited by its mechanical shortcomings, especially when it comes to stiffness and tensile strength when compared to more traditional materials like PMMA (polymethyl methacrylate).In order to improve qualities like osseointegration in implantology, PCL is frequently mixed with other bioactive substances (such hydroxyapatite). Despite these drawbacks, PCL is still a fascinating material in periodontics, implantology, and dental prosthodontics since it provides creative 3D printing and unique restorative design solutions. Its status as a versatile material in contemporary dentistry will likely be cemented by ongoing research that enhances its mechanical qualities and broadens its application in additional clinical contexts.

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