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Fused Deposition Modeling Of Pla Acetabular Liners: A Review Of Manufacturing Parameters, Degradation Mitigation, And Future Prospects

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Abstract

The sustainability of using modified polylactic acid (PLA) produced by fused deposition modeling (FDM) for acetabular liner cup applications in total hip replacement is examined in this work. The study compares PLA with traditional liner materials like ultra-high molecular weight polyethylene (UHMWPE), PEEK, and metals in terms of biocompatibility, mechanical performance, wear, and degradability. It builds on a thorough analysis of additive manufacturing technologies, biomedical FDM applications, and current acetabular liner standards. The review highlights the shortcomings of unmodified PLA, particularly its hydrolytic degradation and inadequate fatigue resistance for permanent load-bearing hip bearings, and explains why compression moulded UHMWPE is still the clinical gold standard, especially with regard to long-term wear and osteolysis. In order to improve the strength, wear resistance, and degradation kinetics of FDM printed PLA components, the paper synthesizes evidence on composite strategies (carbon fiber, graphene, and hydroxyapatite reinforcements), crystallinity control through annealing, surface coatings, and polymer blending (e.g., PLA/PCL). The analysis indicates that while maintaining the benefits of FDM for patient-specific, economical manufacture, reinforced and treated PLA can attain mechanical characteristics and tribological behaviour closer to orthopedic criteria. The study concludes by outlining future options, such as the possibility of 4D printed, shape-morphing liners that adjust to patient anatomy and loading over time, functionally graded PLA-based liners with spatially tailored stiffness, and long-term in vivo evaluation of modified PLA constructs.

Keywords: Acetabular liner; Total hip arthroplasty; Fused Deposition Modeling (FDM); Polylactic acid (PLA); PLA composites; Hydrolytic degradation; Wear and osteolysis; Functionally graded materials; 4D printing; Patient-specific implants

1. INTRODUCTION

1.1 Overview of Additive Manufacturing (AM)

Additive Manufacturing (AM), is also known as 3D printing, has changed the way of designing and manufacturing of products.AM create parts layer by layer directly from 3-

dimensional model unlike to traditional manufacturing processes. In AM material is added layer by layer due to that provide greater design freedom, material waste reduction and improved manufacturing efficiency [1]. AM makes it possible to produce complex shapes that are often too expensive or Impractical, [2]. For creation of visual design models AM makes it possible to produce complex shapes that are often too expensive or Impractical for creation of visual design models. AM began as “Rapid Prototyping in the 1980s”, but from the past three decades it has developed into a reliable, full-scale manufacturing technology [3]. This technology has moved from simple prototyping and now it is used to manufacture end use components for the applications of real world [4]. The progress in AM technology is driven through improvements in material, machine accuracy improvements and improvements in manufacturing speed [5]. By using 3D printing, tooling cost reduces and instead of reshaping traditional supply chain this technology enables on demand local production [6].

3D printing provide customization which provide profit to the niche market without depends on mass production [7]. To achieve sustainable goals of industry, material waste reduction is most important which is possible through Additive manufacturing [8]. Despite its benefits, the main challenge across all major AM categories is to ensure consistent quality control and standardization [5].

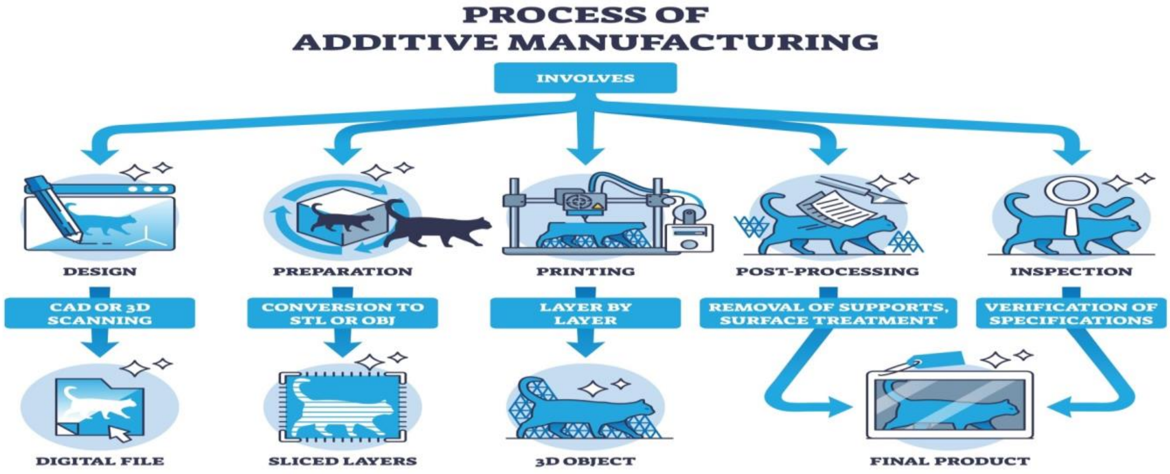

Figure 1: Process of Additive Manufacturing

1.2 Introduction to Fused Deposition Modeling (FDM)

From different AM Technologies, Fused Filament Fabrication (FFF) is widely used for processing of thermoplastics. The filament of thermoplastic is fed through heated nozzle, filament melts and deposited layer by layer which form the final product [9].The paths generated by slicing software fed to printer that convert 3D model into program of instructions (G-Code) for final printing [16]. Flow rate and Viscosity must be proper for strong bonding between layer [10]. As the polymer cools, it fuses on previous layer that form a strong structure [12]. The of FDP parts surface quality and strength depends of machine parameter setting and their optimization [11,13].

Key parameters include:

i. *Layer Thickness:* Balances print time and surface finish.

ii. *Infill Density & Raster Angle:* Control mechanical strength and durability [15].

iii. *Temperature Control:* Prevents warping and ensures dimensional accuracy. [15].

iv. *Print Speed:* Affects productivity but excessive speed can weaken layer bonding. [12].

FDM is affordable and provide material versatility, the material ranging from PLA to high-Performance composites. But still several limitations it has [16]. Due to its layer-by-layer fabrication, FDM parts are inherently weaker along the Z-axis, as interlayer bonds are not as strong as the material within each layer [14]. Additionally, FDM parts often contain small internal voids and exhibit rough surface finishes, which can significantly reduce their performance under heavy loads [17].

1.3 Biomedical Applications & the Challenge of Acetabular Cups

Additive manufacturing technology has provided benefits in the field of biomedical; with AM we can produce patient-specific surgical guides, tissue engineering scaffolds, and implants [22]. In biomedical, Polylactic acid (PLA) is widely used due to its biodegradability and biocompatibility. PLA breaks down into non-toxic lactic acid, which is considered safe for medical use [21]. In modern medicine, PLA is highly versatile and its application ranging from orthopedic fixation to drug delivery systems [22]. 3D printed polymer -based liners widely used in Acetabular liner cup replacement for Total Hip Arthroplasty (THA) [20]. For attaining accurate dimensions and surface finish by using FDM often faces lots of challenges [27]. PLA liner properties can be improved by optimization of FDM parameters. [18]. By adding metal particles and fibers PLA mechanical properties show improvement [19]. PLA/bronze composites show better wear performance, making them more suitable for bearing applications [23]. Similarly, natural fiber and carbon fiber reinforcement also improve the performance of polymers [24].

Although PEEK is considered a high-performance medical polymer, its high cost and processing difficulty make PLA a more accessible option [25]. In contrast, If PLA surface finish and wear behavior properly controlled then it is a cost -effective [26]. This review examines the feasibility of using modified PLA for 3D-printed acetabular liners. It brings together existing research on optimizing printing parameters to improve mechanical and wear performance, and applying material modifications or treatments to control its biodegradability. The aim is to assess whether these combined strategies can make PLA a viable option for long-term implant applications.

2. BACKGROUND

2.1 Fused Deposition Modeling (FDM) and its Biomedical Applications

In various scientific and industrial sectors Fused Deposition Modeling (FDM) is revolution and widely adopted technique. FDM is also known as fused filament fabrication (FFF), in which thermoplastic filament is melted and extruded layer by layer from heated nozzle to fabricate complex three-dimensional objects based on CAD Models [27]. Due to its rapid prototyping capabilities, diverse range of compatible polymeric materials and cost-effectiveness, this technology is highly favorable [28].

FDM has gained significant traction in the biomedical field. In biomedical field materials must be durable, biodegradable and biocompatible [29]. Among thermoplastics, Polylactic Acid (PLA) is bio-based polyester derived from corn starch. It is recognized safe, biocompatible, biodegradable for biomedical and tissue engineering applications [28]. PLA when degrades in human body, it breaks down into water and carbon dioxide which is harmless product [28].

FDM applications in biomedical are growing actively. For creating anatomical models this technology primarily used [30]. Today, for manufacturing of custom orthotics, Prosthetics and for patient -specific surgical instruments, FDM extensively used [30], [31]. 3D -printed guide and tools reduce intraoperative time, improve surgical precision and minimize blood loss in orthopedic surgery [31]. More recently, FDM has transitioned into direct manufacturing that uses patient CT or MRI data to design implants for exact anatomical fit that traditional implants cannot achieve [32]. For bone defect repair, PLA -based FDM scaffolds are promising, but in pure PLA has lack intrinsic oste inductive properties and lack of mechanical strength that required for acetabular liner cups in total hip arthroplasty [33], [34].

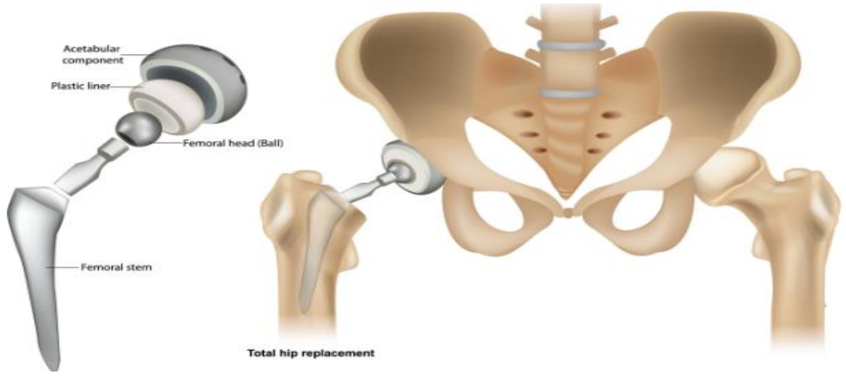

Figure 2: Structural Components of a Total Hip Prosthesis.

To bridge this gap, in PLA the incorporation of additives or reinforcements for improvement in thermal stability, impact toughness and brittleness [34]. Furthermore, FDM processing parameters optimization (e.g., layer thickness, raster orientation, and nozzle temperature) are critical steps toward patient-specific joint replacement and manufacturing durable components [34]. For customized orthopedic implant manufacturing, modified PLA processed via FDM presents a highly feasible and innovative pathway for the future of customized orthopedic implant manufacturing.

2.2 Biomedical Materials and Manufacturing Methods

For developing functional medical devices and implants, appropriate materials selection and manufacturing techniques is the foundation. In orthopedic, material must not only possess mechanical strength but also needs high level biocompatibility and less degradation [35].

2.2.1 3D Printed Materials Used in Biomedical Applications

For fabrication of patient-specific biomedical components 3D printing evolves and introduced a paradigm shift. Polymers, metals, ceramics, and composites are materials that are selected based on end application and physiological demands [35], [36].

In biomedical 3D printing polymers used most widely class of materials. Polylactic Acid (PLA) is the leading polymer for medical applications owing to its FDA-approved biocompatibility, ease of processing, biodegradable and renewable origin. [35], [37].

Polycaprolactone (PCL) also known for its slower degradation, lower melting temperature, ideal for long-term tissue engineering scaffolds [38], [39]. For high load-bearing applications, such as joint replacements and dental implants, metallic biomaterials like titanium alloys (Ti-6Al-4V) and cobalt-chrome are frequently utilized via Selective Laser Sintering (SLS) or Electron Beam Melting (EBM) [39], [40]. These materials face challenges related to "stress shielding" due to their high elastic modulus compared to natural bone but offer superior mechanical integrity [36]. Hydroxyapatite (HA) and tricalcium phosphate (TCP) ceramics are often used in 3D printing to create bioactive scaffolds that promote osseointegration and bone mineral growth [35], [36].

Adding HA or TCP to the PLA matrix increases the compressive strength of the printed part and also reduces the degradation of PLA [35], [41]. These multi-material systems allow for the fabrication of "smart" implants that provide structural support while actively facilitating tissue regeneration [41], [42].

Key properties of common 3D printed biomedical materials that identified in recent literature are summarizes in table given below:

Table 1: Key properties of common 3D printed biomedical materials

Material Type	Material	Key Properties	Primary Application
Thermoplastic	PLA	Biocompatible, Biodegradable	Scaffolds, Orthotics [35]
Metal Alloy	Ti-6Al-4V	High Strength, Corrosion Resistant	Permanent Implants [40]
Ceramic	β-TCP	Osteoconductive, Bioactive	Bone Void Fillers [41]
Composite	PLA/HA	Enhanced Strength, Mineralization	Load-bearing Scaffolds [35], [43]

2.2.2 Manufacturing Methods used in the Biomedical Sector

The transition from subtractive manufacturing to additive manufacturing (AM) has fundamentally altered the production of biomedical devices, moving from mass-produced standardized parts to patient-specific solutions. While several AM techniques exist—such as Stereolithography (SLA) and Selective Laser Sintering (SLS)—Fused Deposition Modeling

(FDM) stands out as the most prevalent method for processing biodegradable polymers like PLA for orthopedic applications [44], [45].

FDM operates on the principle of material extrusion, where a thermoplastic filament is heated to a semi-liquid state and deposited layer-by-layer. The structural integrity and mechanical performance of the final biomedical component, such as an acetabular liner, are heavily dependent on several critical processing parameters: nozzle temperature, bed temperature, printing speed, layer height, and raster orientation [46], [47]. Research indicates that for PLA-based implants, a raster angle of 0°/90° or a concentric pattern is often preferred to optimize load distribution and minimize anisotropic behavior [47]. Furthermore, reducing layer thickness has been shown to improve surface finish and decrease porosity, which is vital for minimizing bacterial adhesion on medical surfaces [48].

To address the mechanical requirements of load-bearing joints, the manufacturing process often begins before the printing stage through the production of "modified" filaments. This typically involves Twin-Screw Extrusion (TSE) to homogenize PLA with reinforcements such as hydroxyapatite (HA), carbon fibers, or natural particles [49]. Achieving a uniform dispersion of these additives is critical; poor mixing can lead to nozzle clogging during FDM or create "stress concentrators" within the printed liner that lead to premature failure [50]. Recent advancements in "multi-material" FDM now allow for the simultaneous deposition of different materials, enabling the creation of functionally graded acetabular cups that feature a porous outer layer for bone in growth and a dense, low-friction inner liner [45].

In the context of acetabular liners, the manufacturing precision must be sub-mill metric to ensure a "press-fit" stability within the pelvic bone. Post-processing techniques, including thermal annealing or chemical vapor polishing, are frequently employed to enhance the crystalline of the PLA and reduce the "staircase effect" inherent to FDM, thereby improving the tribological interface of the bearing surface [47], [43].

2.3 Acetabular Liner Cup Materials

In total hip arthroplasty (THA), acetabular liner is a critical component and it is a bearing surface that articulates with femoral head. Its function to reduce the friction and distribute the load across the pelvic interface [51], [21]. For liners, ultra-high-molecular-weight polyethylene (UHMWPE) use due to its toughness and low friction. However, UHMWPE is prone to abrasive wear and adhesive wear, which generates sub-micron-sized debris [51],[52]. This wear debris often causes of long-term implant failure [30], [52].

To mitigate these issues, highly cross-linked polyethylene (HXLPE) was introduced, provides a significant reduction in volumetric wear [53], [52]. Despite these improvements, the quest for patient-specific implants and the need to address "stress shielding" where the high stiffness of metallic shells prevents natural load transfer to the bone has driven research toward additive manufacturing (AM) and alternative polymeric composites [20],[54].

Polylactic Acid (PLA) has emerged as excellent process ability in Fused Deposition Modeling (FDM) and excellent process ability for orthopedic components [50]. Recent studies have focused on the modification of PLA to enhance its structural integrity for use as an acetabular liner. For instance, optimizing FDM processing parameters—such as layer thickness, nozzle temperature, and raster orientation (0°)—has been shown to increase the ultimate tensile strength of PLA to approximately 51 MPa and Young's modulus to 3400 MPa, making it more comparable to conventional implant plastics [21].

A notable study utilized date pit particles as a reinforcement in a PLA matrix, finding that a 10 wt.% loading fraction enhanced compressive strength and stiffness, although it slightly reduced elongation and toughness [50]. Finite element analysis (FEA) has validated that the modified PLA composites can safely support physiological weights ranging from 70 to 90 kg while maintaining manageable contact stresses [21],[50]

Tribological performance remains a challenge, as coefficients of friction around 0.302 recorded in additively manufactured plastic liners, which is higher than the values seen in conventional bearings [55]. The ability to manufacture porous, patient-specific acetabular liners using modified PLA presents a promising pathway to improve the anatomical fit of hip prostheses and reduce surgical time [20],[56].

Table 2: Comparison of Biomedical & Acetabular Materials and Manufacturing Methods

Ref	Category	Material(s)	Manufacturing Method	Key Findings & Properties
[21]	Acetabular	PLA (Optimized)	3D Printing (FDM)	Young's Modulus: 3400MPa; Tensile: 51MPa. Raster angle 0∘ is optimal for load-bearing.
[50]	Acetabular	PLA / Date Pit	3D Printing (FDM)	10wt.% particles improve stiffness and compressive strength for body weights up to 90kg.
[52]	Acetabular	UHMWPE (GUR 1050)	CNC Milling	Standard for bearing surfaces; milling provides ASTM-compliant surface roughness (Ra<0.5μm).
[57]	Acetabular	Titanium (Ti6Al-4V)	3D Printing (SLM/EBM)	Porous lattice structures mimic bone; superior osseointegration compared to bulk forging.
[58]	Acetabular	PEEK (Medical Grade)	3D Printing (FDM/FFF)	Elastic modulus (3.6GPa) closer to bone; reduces stress-shielding; high dimensional stability.
[33]	Bone Scaffold	PLA / Nano β-TCP	3D Printing (FDM)	Bioactive; β-TCP neutralizes acidic degradation and promotes cell growth.
[49]	Bone Scaffold	PLA / Hydroxyapatite	3D Printing (FDM)	Hybrid composite improves hardness and mimics natural bone mineral phases.

[59]	Implant Shell	Porous Tantalum	3D Printing (EBM)	Ideal for complex Paprosky 3B defects; enables 92% bone ingrowth at interface.
[40]	Articulation	Cobalt-Chrome (CoCr)	Conventional (Casting)	Extreme wear resistance but higher metal ion release risk than polymer liners.
[32]	Fixation	Magnesium Alloys (Mg)	3D Printing (SLS)	Fully biodegradable; avoids secondary surgery for implant removal.
[60]	Tissue Eng.	PCL / Collagen	Bioprinting (Extrusion)	Soft tissue repair; supports high cell proliferation and multiplication.
[37]	Drug Delivery	PLGA (Lactic-glycolic)	3D Printing (SLA)	Tunable degradation rates for controlled time-dependent drug release.
[11]	Orthotics	PETG / TPU Blend	3D Printing (FDM)	High impact toughness and flexibility for customized wearable medical devices.
[20]	Bearing	Cross-linked PE	Isostatic Molding	Improved wear resistance over standard UHMWPE through radiation cross-linking.
[61]	Dental	Zirconia (Ceramic)	3D Printing (DLP)	High aesthetic value and fracture toughness; low thermal conductivity.
[34]	General	PLA (Impact Modified)	3D Printing (FDM)	Additives reduce the natural brittleness of PLA for high-performance surgical tools.
[27]	Support	Stainless Steel (316L)	CNC / Machining	High strength and low cost, but heavy; prone to stress-shielding in long-term use.
[39]	Bio-inks	Hydrogels (Cell-laden)	Extrusion Bioprinting	Mimics the Extra-Cellular Matrix (ECM); maintains living cell viability post-print.

3 METHODOLOGY

3.1 PLA in Load-Bearing Orthopedics

Polylactic Acid (PLA) has excellent biocompatibility, a non-toxic degradation profile, and printability via Fused Deposition Modeling (FDM); due to these, PLA garnered significant attention in orthopedic applications [55], [28]. For acetabular liner in Total Hip Arthroplasty (THA), use of PLA severe physiological and biomedical challenges. The first limitation is degradation of PLA and generates lactic acid which leads implant loosening [52], [19]. Therefore, to preserve structural integrity, need to retard degradation of PLA.

The degradation of PLA is governed by the hydrolytic scission of its ester backbone in a physiological environment (pH 7.4, 37°C). Water molecules diffuse into the amorphous regions of the polymer matrix, cleaving the long molecular chains into shorter oligomers and eventually lactic acid monomers [62]. This process is autocatalytic; the carboxylic acid end-groups generated during hydrolysis further accelerate the localized scission of remaining ester bonds [63]. Through various physical and chemical modifications, researchers sought to mitigate water ingress and neutralize acidic by-products to adapt PLA for long-term load-bearing applications.

3.2 Strategies for Degradation Reduction

3.2.1. Thermal Annealing and Crystallinity Modulation

PLA crystalline regions are highly resistant to water diffusion as compared to their amorphous domain. A tortuous path is created by increasing its degree of crystalline, which restricts the permeation of aqueous physiological fluids.

FDM printed PLA component thermal annealing at a temperature between the glass transition and melting point (90°C to 110°C) allows polymer chains to reorganize into tightly packed crystalline lamellae [21],[34].

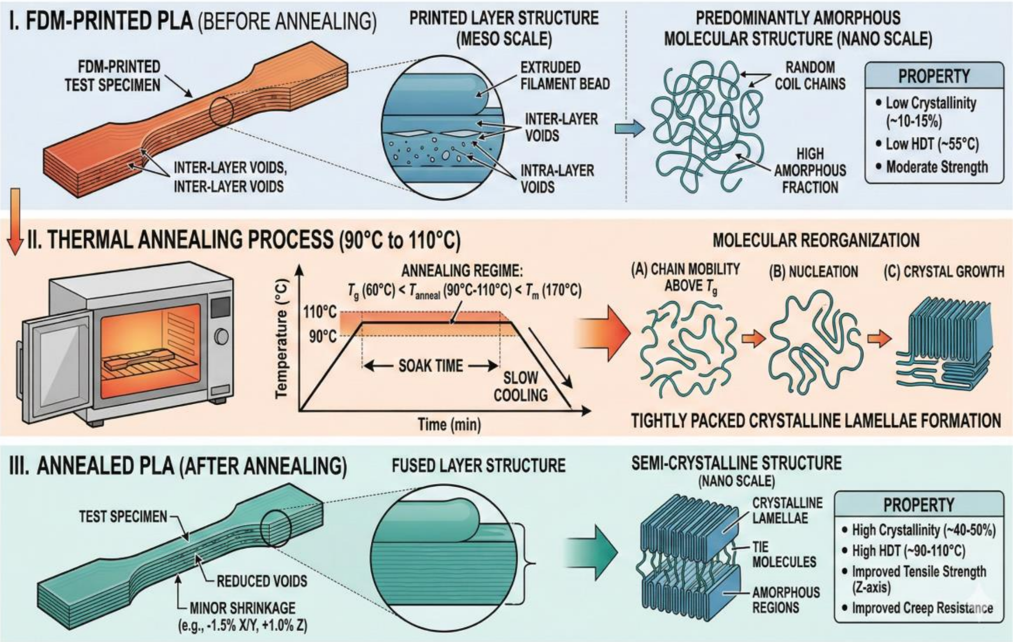

Figure 3: Microstructural Evolution of FDM-Printed PLA Post-Thermal Annealing

Shielding the ester bonds from premature hydrolysis by the incorporation of nucleating agents during the filament compounding stage [64].

3.2.2. Incorporation of Hydrophobic Additives and Bioceramics

Improvement in the poor tribological performance (wear resistance) of PLA, and acting as a barrier against degradation, is possible by integration of reinforcing fillers. A physical moisture barrier is created within the polymer matrix by the addition of hydrophobic agents, such as carbon nanotubes (CNTs) or graphene derivatives [50].

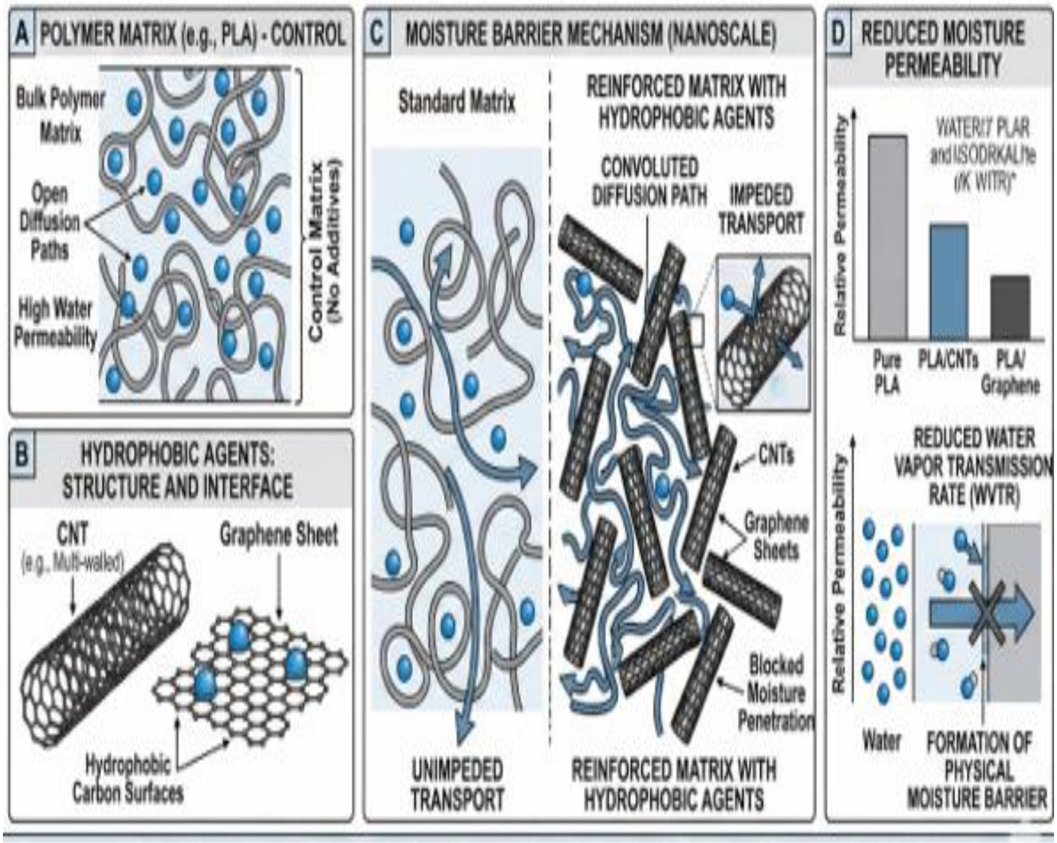

Figure 4: Moisture Barrier Mechanism in Reinforced PLA Composites

Adding particles like Hydroxyapatite (HAp) or Magnesium (Mg) prevents the material from breaking down quickly. They block water absorption and neutralize harmful acids that form during degradation, stopping the decay process in its tracks [65].

3.2.3. Surface Coating and Encapsulation Techniques

In joint bearings, advance deposition is employed as high-precision dimensional tolerance is essential.

A hermetic seal is formed by applying ultra-thin, pinhole-free layers of metal oxides (e.g., Titanium Dioxide, TiO2) via Atomic Layer Deposition (ALD). This effectively isolates the underlying PLA matrix from immediate contact with enzymatic agents and synovial fluids without compromising the macro-mechanics of the FDM print [66]

Blending PLA with or dip-coating it in, slower-degrading hydrophobic polymers like Polycaprolactone (PCL) has been proven to form a protective external skin that extends the implant's operational lifespan in vivo [67] [68].

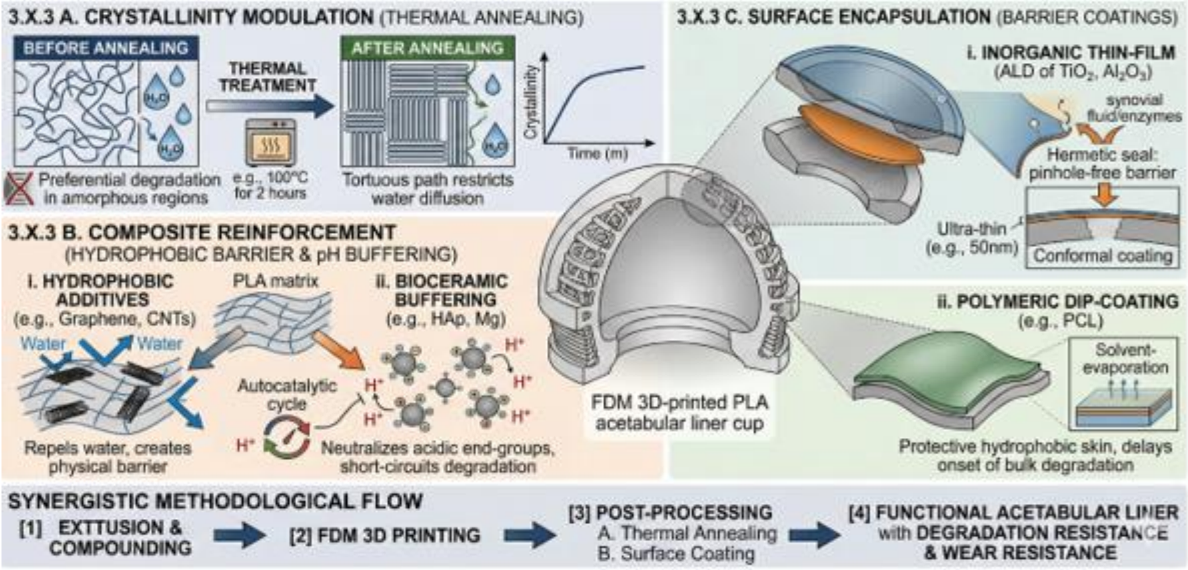

Figure 5: Methodology for reducing degradability of PLA acetabular liner

No single invention is sufficient to Prepare PLA for rigorous environment such as THA joint.

During extrusion phase, need to combine hydrophobic and buffering composite fillers and for maximum density optimize FDM printing parameters. [21][50] and alongside surface coatings as a barrier may be employ with post-processing thermal annealing. These modifications are necessary for hydrolytic stability and wear resistance which is the requirement for an acetabular liner.

4. CONCLUSION AND FUTURE SCOPE

4.1 Conclusion

Fused Deposition Modeling (FDM) for acetabular liner cups in Total Hip Arthroplasty (THA) by using modified Polylactic Acid (PLA) is evaluated in the literature. The following conclusions are drawn on the bases of material science, degradation mitigation strategies, and comprehensive review of manufacturing parameters:

i. On printing parameters acetabular liner structural integrity depend. For reducing the "staircase effect" and maximizing mechanical strength need 0°/90° raster orientation and minimized layer thickness. Therefore, for producing patient-specific orthopedic implant, FDM is highly viable method.

ii. For joint bearing, pure PLA has less impact toughness and wear resistance therefore to improve compressive strength and stiffness reinforcements of Date Pit particles (10 wt.%), Hydroxyapatite (HAp), and Carbon Fibers. These composites make them cost-effective alternative to PEEK or UHMWPE as they support physiological loads of 70–90 kg.

iii. PLA implants hydrolytic degradation can be managed by thermal annealing (90°C–110°C) increases crystallinity and create barrier against water. Moreover, the incorporation of bio ceramics such as β-TCP fulfills two functions: it neutralizes acidic degradation byproducts and facilitates osseointegration.

iv. PLA liners can achieve the dimensional precision and hydrolytic stability by optimized FDM settings with surface treatments like PCL dip-coating or Atomic Layer Deposition (ALD) which is required for "press-fit" surgical stability.

4.2 Future Scope

Although the existing research provides a solid basis, the shift from laboratory prototypes to clinical application necessitates additional exploration in the subsequent areas:

i. "4D printing" research might be explored, in which the acetabular liner reacts to physiological stimuli (such as pH or temperature changes) to release growth factors or anti-inflammatory medications at the implant site.

ii. To address the issue of inconsistent quality control, it would be beneficial to use Machine Learning (ML) algorithms to determine the best mix of infill density, nozzle temperature, and annealing time for 3D-printed medical components. This would further standardize their quality.

iii. To minimize friction against the femoral head, it is important to produce an ASTM-compliant surface roughness, which could be achieved by combining FDM with post-print CNC machining or chemical vapor polishing.

iv. Applying different non-biodegradable elements by coating reduces PLA's degradability in body fluids environments. These coatings prevent PLA from coming into direct touch with body fluids.

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