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EVALUATION OF BIOCOMPATIBILITY AND ANTIMICROBIAL PROPERTIES OF BIO-COMPOSITES FOR KNEE CAP APPLICATIONS

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ABSTRACT
The growing demand for sustainable and biocompatible materials has driven interest in bio-composites for healthcare applications. The poly (lactic acid) (PLA) is selected for its biodegradability, mechanical strength, and non-toxic in nature, while Blepharis maderaspatensis enhances antimicrobial and anti-inflammatory properties of the bio-composite. This study focuses on developing PLA bio-composite blended with Blepharis maderaspatensis to develop the external knee cap applications, designed for safety. The PLA blended with 1%, 2%, and 3% concentrations of Blepharis maderaspatensis are tested to determine the optimal formulation for safety and performance. Material characterization studies of Blepharis maderaspatensis is conducted for functional group, chemical structure identification and thermal stability by using Fourier Transform Infrared Spectroscopy (FTIR) and Thermogravimetric Analysis (TGA) to ensuring its compatibility with the PLA matrix. The cytotoxicity and antimicrobial tests are performed to confirm the biocompatibility of the prepared sample. The findings are demonstrated that PLA-Blepharis maderaspatensis bio-composites offer lightweight, durable, and antimicrobial solutions, making them highly suitable for external knee cap and contributing to the development of sustainable and reliable materials for sports safety equipment.

Keywords:
Polylactic Acid (PLA), Blepharis maderaspatensis, Bio-Composites, Sports Safety, Kneecap, Material Characterization, Biocompatibility

I. Introduction
The increasing global focus on sustainability and biocompatibility has fostered a growing interest in bio-composites for applications in healthcare and safety. External knee caps, often used in sports such as skating and cycling, require materials that are lightweight, durable, and antimicrobial to ensure user safety and comfort. Polylactic acid (PLA) is widely recognized for its excellent biodegradability, mechanical strength, and non-toxic nature, making it a preferred base material for bio-composites.
Blepharis maderaspatensis, a medicinal plant known for its antimicrobial and anti-inflammatory properties, offers a promising additive for enhancing the functional characteristics of PLA-based composites. Previous studies on Blepharis maderaspatensis have highlighted its thermal stability and active functional groups, essential for material compatibility and performance. However, the application of PLA-Blepharis maderaspatensis composites in external safety gear remains underexplored.
This research focuses on the development of PLA bio-composites blended with varying concentrations (1%, 2%, and 3%) of Blepharis maderaspatensis. The study aims to determine the optimal composition for external knee cap applications, emphasizing material characterization, biocompatibility, and antimicrobial properties.

II. Literature

Polylactic acid (PLA) and its composites have gained attention due to their biodegradability, biocompatibility, and excellent processability. With the depletion of petroleum resources and increasing environmental awareness, PLA is being explored as an alternative to traditional plastics. PLA-based materials are particularly promising in biomedical applications and sustainable manufacturing (1). The incorporation of natural fibers into PLA-based composites has shown potential in medical applications such as implants and prosthetics. Biocompatibility and mechanical properties are critical factors influencing their usability in these fields (2). PLA - based bio-composites offer sustainable properties and reduced environmental impact. Studies have explored methods of fabrication and characterization, focusing on the incorporation of natural fibers to improve mechanical, thermal, and biodegradation properties. These composites are especially useful in medical and packaging sectors (3). Kneecap pain is a common issue among cyclists, often resulting from overuse, improper posture, or muscle imbalance. Addressing patellofemoral pain syndrome through proper equipment and training adjustments can prevent injuries and enhance performance (4). Advancements in PLA-based composites have improved their suitability for medical applications such as bone scaffolds, wound healing, and tissue engineering. Natural fillers and reinforcements enhance the properties of PLA, making it more effective in medical devices while reducing environmental impact (5). Research into advanced PLA composites emphasizes the use of additives like bioactive agents to enhance mechanical strength, biodegradation rate, and biocompatibility. These advancements have led to increased applications in orthopedic implants, drug delivery systems, and tissue engineering (6). Enhancing the thermal and mechanical properties of PLA-based bio-composites has expanded their use in biomedical fields. Incorporating natural fibers and fillers improves their performance under physiological conditions, making them suitable for implants, prosthetics, and drug delivery systems (7). Fillers play a crucial role in improving the mechanical, thermal, and biological properties of PLA composites. The use of natural fibers, nanoparticles, and bioceramics has demonstrated potential for applications in medical devices, particularly those requiring high mechanical strength and biocompatibility (8).

Recent advances in polymer matrix composites, including PLA-based materials, have enhanced their applicability in the biomedical field. Improvements in mechanical strength, biodegradability, and biocompatibility have made these materials suitable for medical implants, tissue engineering, and drug delivery systems (9). PLA composites are widely studied for their biodegradability, biocompatibility, and mechanical performance. The effects of reinforcement materials and processing techniques on the structure-property relationships of PLA have been comprehensively analyzed to address challenges in demanding medical applications (10). The growing use of PLA-based composites in biomedical applications is driven by their biodegradable and biocompatible nature. Innovations in composite fabrication have improved their mechanical strength and long-term stability for use in orthopedic devices, drug delivery, and tissue engineering (11). The development of PLA composites has focused on enhancing their functionality in medical implants such as bone and cartilage. The incorporation of reinforcements and bioactive agents has improved the performance and customization potential of these materials (12).

PLA-based composites provide environmental benefits, particularly in reducing plastic waste in medical and packaging applications. Their biodegradability and potential to reduce pollution make them a sustainable alternative to conventional plastics (13). The mechanical properties of PLA-based composites are crucial for their application in medical fields like implants and prosthetics. Natural fibers, nanoparticles, and other reinforcements are used to enhance strength and durability, addressing challenges for long-term use (14). PLA composites are increasingly utilized in orthopedic applications such as bone repair and reconstruction. Research has focused on improving their mechanical properties, biodegradation rates, and biocompatibility to meet the specific needs of patients (15). Soft tissue engineering has benefited from the use of PLA-based composites, which enhance cell growth and tissue integration. The addition of bioactive agents and natural fibers offers promising solutions for regenerating soft tissues like skin, nerves, and muscles (16). Biodegradable polymers, particularly PLA composites, are advancing medical applications by breaking down safely in the body. These materials have been applied in drug delivery, wound healing, and tissue regeneration, showcasing significant progress (17). The biocompatibility and customizability of PLA composites have driven their widespread use in biomedical applications. Applications such as drug delivery systems, tissue engineering, and surgical implants highlight ongoing challenges and future directions in the field (18). Advanced bio-composites, particularly those using PLA, have seen rapid growth due to their sustainability and versatility. These materials are increasingly used in implants, prosthetics, and drug delivery systems, with improved mechanical and biological performance (19). The development of PLA-based bio-composites provides sustainable solutions for medical applications. Natural fibers and bioactive agents have been incorporated to enhance the mechanical, thermal, and biological properties of PLA, positioning these composites as key materials for environmentally friendly devices (20).

2.1 Materials and preparation Polylactic acid (PLA) pellets and Blepharis maderaspatensis powder were used as primary materials. The herbal powder was subjected to FTIR and TGA to determine its functional groups and thermal stability. Three formulations, containing 1%, 2%, and 3% of Blepharis maderaspatensis by weight, were blended with PLA using a single-screw extruder. The extruded composites were 3D-printed into standard shapes for subsequent testing.

2.2 Material characterization FTIR Analysis: Blepharis maderaspatensis powder was analysed using FTIR to identify functional groups and chemical compatibility with PLA.

TGA: Thermal stability of Blepharis maderaspatensis was assessed to ensure performance during composite processing.

2.3 Biocompatibility tests Cytotoxicity Test: Prepared samples were subjected to in vitro cell culture assays to evaluate their compatibility with biological tissues.

Antimicrobial Activity: The composites were tested against Escherichia coli and Staphylococcus aureus to measure bacterial inhibition.

III. Conclusion

FTIR Analysis: The FTIR spectrum of Blepharis maderaspatensis powder confirmed the presence of significant functional groups, including hydroxyl (OH) and carboxyl (C=O) groups. Peaks observed at 3857 cm^{-1} and 588 cm^{-1} represent phenolic and aliphatic compounds, respectively. These functional groups enhance the antimicrobial properties and establish compatibility with the PLA matrix. TGA Analysis: Thermogravimetric analysis revealed the thermal stability of Blepharis maderaspatensis up to 300°C, indicating its suitability for composite processing at standard extrusion and 3D printing temperatures. The degradation profile demonstrated that the herbal additive could withstand the high-temperature conditions without significant loss of functional properties.

The test conducted on all formulations demonstrated excellent cell viability. Among the formulations, the 2% Blepharis maderaspatensis composite exhibited the most favourable results, with minimal cytotoxic effects and consistent compatibility with biological tissues. This suggests that the incorporation of Blepharis maderaspatensis enhances the safety profile of PLA composites for external applications. The antimicrobial tests showed that all PLA-Blepharis maderaspatensis composites effectively inhibited the growth of gram-positive Staphylococcus aureus and gram-negative Escherichia coli. The 3% formulation exhibited the highest antimicrobial efficacy, demonstrating significant bacterial resistance. However, this formulation showed slight compromises in material processing and biocompatibility compared to the 2% formulation, which provided an optimal balance of properties.

Overall Performance, The PLA-Blepharis maderaspatensis bio-composites demonstrated excellent performance in all tested aspects, with the 2% formulation emerging as the most balanced candidate. Its combination of biocompatibility, thermal stability, and antimicrobial properties makes it ideal for external knee cap applications, particularly for sports safety gear. These findings contribute to advancing sustainable material development for practical, high-performance applications.

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