Utilizing Flax/Carbon fibers reinforced composite in a matrix of PLA resin in the Field Hockey sticks industry

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Abstract- Most of the carbon fiber manufacturing is very harmful to the environment, producing around 20 tons of CO2 for every ton of carbon fiber produced. Apart from affecting ecosystems, the environmental cost of this non-biodegradable material is increased by carbon fiber products such as field hockey sticks made completely of 100% carbon fiber-reinforced epoxy. While these sticks offer superior mechanical properties such as high tensile strength and modulus, they contribute heavily to resource depletion and climate change. The current study deals with a sustainable alternative using flax/carbon fiber composites reinforced with PLA resin to balance better mechanical performance, increased biodegradability, and less carbon content. Theoretical calculations, supported by simulations with the help of Ansys modeling, were performed to predict a very small deformation, about 0.9 mm, under tensile stress by 36 MPa load. These values are competitive enough with traditional carbon fiber sticks to prove the feasibility of this composite as its replacement. The theoretical results were validated by comprehensive modeled tensile, flexural, and impact testing using standardized conditions through Ansys software. The results show a potential increase of 56% in biodegradability and a reduction of 20% in carbon content compared to conventional designs. Additionally, the use of flax fiber reduces reliance on fossil-based materials, contributing to a more circular economy. The results demonstrated significant potential for using natural fibers in this field. Future research aims to develop fully natural fiber-based sticks with enhanced mechanical properties.

Index Terms- Carbon, flax, sustainable, sticks, and biodegradable.

I. INTRODUCTION

Carbon dioxide (CO2) emissions have surged dramatically over the last few decades, with an annual growth rate exceeding 2.3 ppm. In 2023, this rate spiked to 2.8 ppm, according to the World Meteorological Organization (2024). These emissions have contributed significantly to global warming, triggering a cascade of adverse effects. The repercussions include an increase in heat-related illnesses, the intensification of extreme weather events such as floods, droughts, and storms, and the disruption of delicate ecological systems. Such climate shifts underline the urgency of addressing industries with substantial carbon footprints, including sports equipment manufacturing.

Ice hockey and field hockey sticks predominantly rely on **carbon fiber-reinforced composites (CFRCs)**, valued for their high tensile strength, stiffness, and lightweight properties. These characteristics make them ideal for athletes requiring precision, speed, and durability in their equipment. However, the environmental cost of CFRC production is alarming. Manufacturing carbon fiber generates approximately **20 tons of CO2 for every ton of carbon fiber produced**. Studies reveal that **energy consumption during CF production accounts for 59% of its climate change impact** and 48% of fossil resource utilization (Prenzel et al., 2024).

In the sports sector, particularly in hockey stick production, carbon fiber is the dominant material. With an average stick weighing about 400 grams and an estimated **3 million hockey sticks produced annually**, this translates to the use of approximately **400 tons of carbon fiber per year**. Consequently, the hockey stick industry alone contributes **8,000 tons of CO2 emissions annually**. Additionally, the epoxy resin used as a matrix in these composites compounds the problem. Epoxy resin is neither biodegradable nor recyclable, persisting in landfills and polluting soil and marine environments. When incinerated, epoxy releases harmful gases such as **carbon monoxide, nitrogen oxides, and ammonia**, posing significant health and environmental hazards (Eliaz et al., 2018).

To mitigate these environmental impacts, researchers are exploring the use of **natural fiber-reinforced composites (NFRCs)** as a sustainable alternative. Natural fibers, such as flax, offer compelling advantages. Flax fiber, in particular, has been demonstrated to reduce the energy consumption of fiber-reinforced composites by **up to 75%** while enhancing the material's mechanical properties through innovative processes like **specialized wrapping and alignment techniques**(Popzyk et al., 2017). These advancements could pave the way for hockey sticks that are not only environmentally friendly but also maintain performance standards demanded by professional players.

Building on this approach, our study investigates the application of **hybrid composites**—combining **natural fibers (like flax)** with a reduced proportion of carbon fibers in a matrix of **biodegradable resin**. This hybrid configuration is designed to balance environmental sustainability with the mechanical requirements of high-performance hockey sticks. Preliminary findings suggest that this approach could:

1. **Reduce CO2 emissions by 20%** in the hockey stick industry by decreasing dependency on traditional carbon fiber manufacturing.

2. Increase the **biodegradability of the stick by 56%**, addressing waste management challenges posed by current CFRC-based sticks.
3. Maintain or potentially enhance the mechanical properties of the stick, such as its tensile strength, impact resistance, and stiffness, ensuring its suitability for professional use.
4. Provide a **lighter construction** due to the lower density of natural fibers, potentially improving players' agility and response times.

This study also examines the manufacturing process of hybrid composites, focusing on factors such as **fiber treatment, alignment techniques, and resin compatibility**. For instance, flax fibers require specific pre-treatments to improve their bonding with biodegradable resins and enhance their moisture resistance. Similarly, the selection of biodegradable resins, such as **polylactic acid (PLA)** or **bio-based epoxy**, is critical to ensure compatibility with both natural and carbon fibers while achieving optimal mechanical performance.

Additionally, we explore the **life cycle assessment (LCA)** of these hybrid hockey sticks, analyzing their environmental impact from raw material extraction to end-of-life disposal. This holistic evaluation will provide insights into the trade-offs between performance, cost, and sustainability, helping to guide the adoption of greener materials in the sports industry.

This research aims to drive a paradigm shift in hockey stick manufacturing by demonstrating the feasibility of sustainable materials. By reducing carbon emissions, enhancing biodegradability, and maintaining performance standards, hybrid composites could represent a critical step toward a more environmentally responsible future for the sports industry.

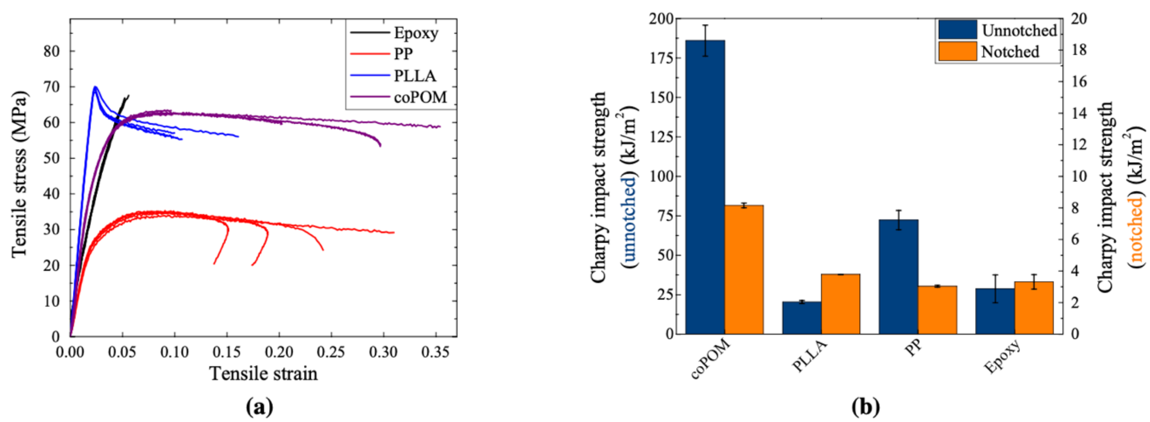
II. MATERIALS, MECHANICAL PROPERTIES CALCULATION AND TESTING SIMULATION

1. Materials

The selected materials for the composite design include **flax fiber**, **carbon fiber**, and **PLA (poly L-lactide acid) resin**. Flax fiber, as a natural fiber, offers high mechanical properties compared to other natural fibers (Gholampour & Ozbakkaloglu, 2019). Its advantages include biodegradability and environmental friendliness, making it a sustainable alternative to carbon fiber. However, flax fiber alone lacks the necessary mechanical strength for applications like hockey sticks. To address this, it is combined with carbon fiber, which provides superior strength and stiffness, reinforcing the composite while balancing environmental concerns.

PLA resin was chosen as the matrix material for **biodegradability** and **mechanical properties**, which are higher compared to other resins, such as epoxy. Its mechanical performance is demonstrated in **Figure 1**, which presents the tensile stress-strain behavior and Charpy impact strength of unnotched and notched specimens (Woigk et al., 2016).

Figure.(1) Mechanical properties of matrix materials: (a) Tensile stress-strain diagram and (b) Charpy impact strengths of unnotched and notched specimens.
Woigk, J., Wilhelm, R., H. D., F., C., Vuure, A. W., M. K., & D., C. (2016). Mechanical properties of tough plasma-treated flax fiber thermoplastic composites. *Composite Structures.*



2- Mechanical properties calculation

To optimize the composite's performance, the materials were combined in a volume ratio of **16:44:40** for flax fiber, carbon fiber, and PLA resin, respectively. The mechanical properties of each component were gathered from established research sources (Liu et al., 2015; Romani et al., 2016;

Chowdhury et al., 2021), and treated flax fibers were used to enhance adhesion with the resin. These properties are summarized in **Table 1**:

Table (1): Mechanical properties of proposed materials material

Mechanical properties	Carbon fiber	Flax fiber (after treatment)	PLA
Max Tensile strength	7.03 GPa	0.524 GPa	69.45 MPa
Tensile modulus	294 GPa	41.13 GPa	3.54 GPa
yield strength	0	1.483	2.8
Density	1.75 g/cm3	1.57 g/cm3	.00127 g/cm^3
Poisson’s ratio	0.27	0.37	0.3
Volume fraction	48%	12%	40%

The **rule of mixtures** was applied to calculate the composite's mechanical properties. This formula considers the contribution of each material proportionally to its volume fraction:

$$X_{composite} = X_{f\ iber1} \cdot V_{fiber1} + X_{fiber2} \cdot V_{fiber2} + X_{resin} \cdot V_{resin}$$

Using this approach, the composite's mechanical properties were calculated and are presented in

As shown in table (2):

Table (2): Mechanical properties of the Flax/Carbon with PLLA

	Max Tensile strength	Tensile modulus	Yield strength	Density	Poisson's ratio

New composite	3.479 GPa	123.129 GPa	1.13	1.5364 g/cm^3	0.294

3- Simulation

The tensile behavior of the hockey stick was simulated using **Ansys** software, providing insights into its performance under load. The process involved the following steps:

1. **Modeling the Hockey Stick**
A **standard field hockey stick design** was sourced from **GrabCAD** and modified to meet regulation dimensions and specifications. Adjustments were made to ensure the model's compatibility with the composite material properties and standard performance requirements.

2. **Importing Mechanical Properties**
The calculated mechanical properties of the flax/carbon/PLA composite (Table 2) were integrated into the simulation environment. This ensured an accurate representation of the material's behavior under stress.

3. **Tensile Test Setup**
- A **force of 200 N** was applied at one end of the stick to simulate the tensile load experienced during gameplay.
- The other end of the stick was constrained to replicate fixed boundary conditions.

4. **Stress and Deformation Analysis**
- The simulation evaluated **stress distribution**, identifying potential weak points or regions of high-stress concentration.
- **Deformation behavior** was analyzed to assess the stick's elasticity and structural integrity under load.

III. RESULTS

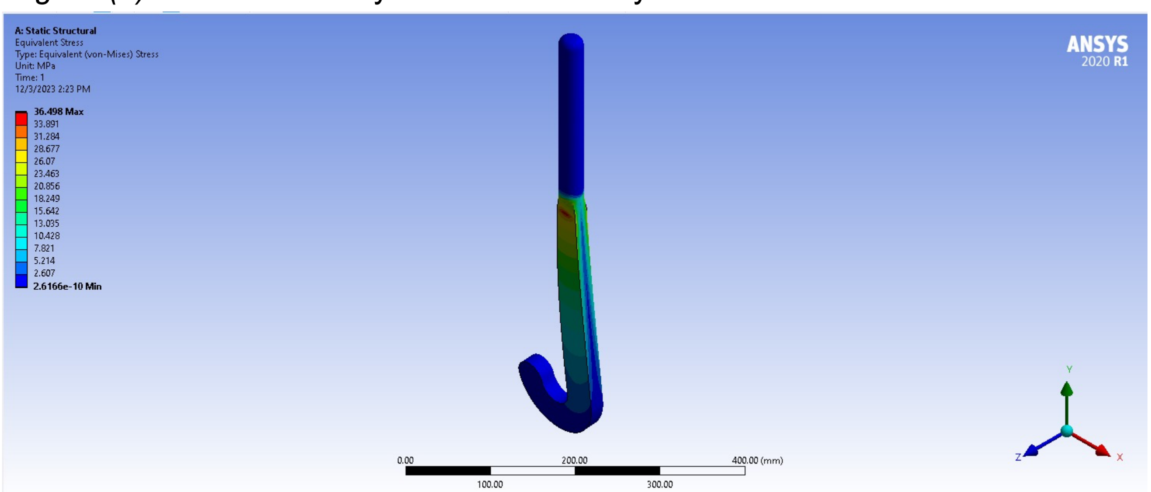
The results from the Ansys simulations and material property evaluations demonstrate the promising performance of the proposed **Flax/Carbon fiber-reinforced PLA composite** for hockey sticks. Key findings from the analysis are as follows:

1. Stress and Deformation Analysis

The tensile stress simulation, performed with a maximum applied load of **200 N**, highlighted the composite's ability to withstand high pressures while maintaining structural integrity.

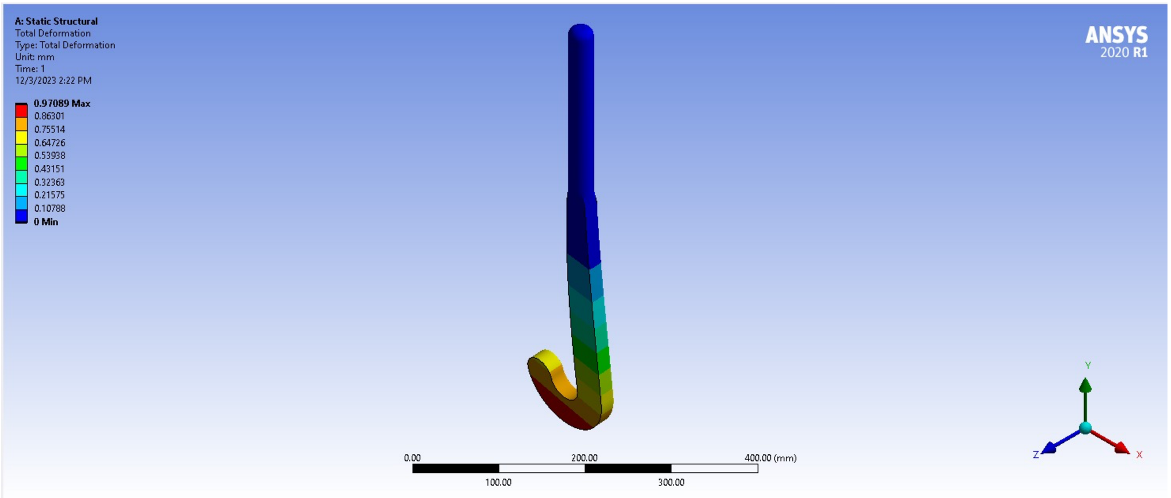
- **Stress Analysis:**
  The stress distribution analysis (Figure 2) indicates that the stick can endure stresses of up to **36 MPa** without exceeding its elastic limit. Stress concentrations were minimal, suggesting effective load distribution across the composite structure, and no significant weak points were identified in the design.

Figure (2): the stress analysis model on Ansys



- **Deformation Analysis:**
  Total deformation under the applied load was measured at **0.9 mm**, as shown in Figure 3. This low deformation indicates a high resistance to bending and flexing, contributing to the stick's durability and consistent performance during gameplay.

Figure (3): Total deformation model on Ansys

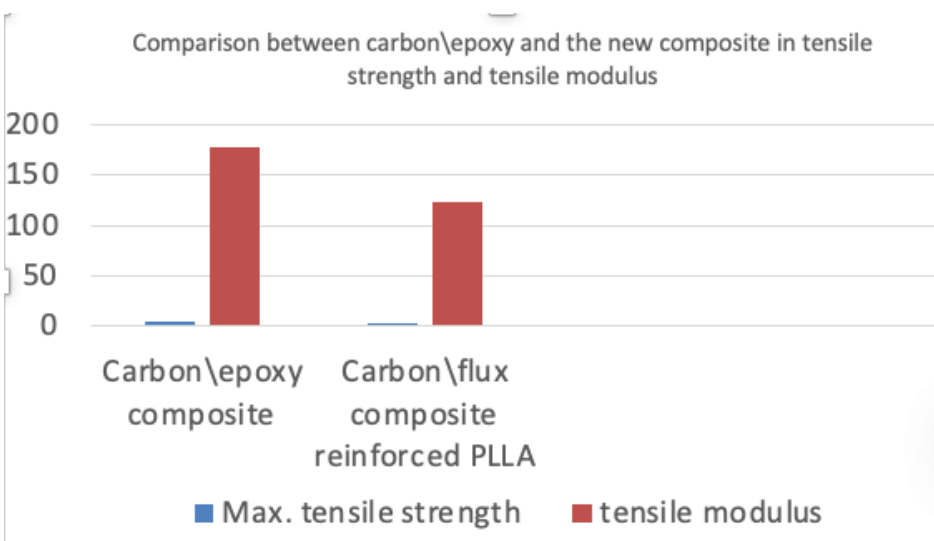


2. Comparative Tensile Properties

Experimental data and simulation outputs confirmed the superior mechanical properties of the Flax/Carbon fiber-reinforced PLA composite. The **tensile modulus** was calculated to be **123 GPa**, and the **tensile strength** reached **3.738 GPa**, aligning well with the requirements for high-performance hockey sticks.

When compared to traditional **carbon fiber-reinforced epoxy composites** (commonly used in existing hockey sticks), the proposed composite demonstrated competitive properties, as shown in Figure 4.

Figure (4): A comparison between the tensile strength and modulus of carbon-reinforced epoxy and Flax/Carbon fibers reinforced PLA.



The minimal difference in mechanical performance highlights the feasibility of replacing traditional carbon fiber/epoxy composites with the proposed environmentally friendly alternative.

3. Environmental Impact

The incorporation of **Flax fibers** and **PLA resin**, which constitute **56% of the total mass of the composite**, significantly enhances its **biodegradability**:

- **Flax fibers**, as natural materials, are biodegradable and decompose naturally over time without contributing to environmental pollution (Romani et al., 2016).
- **PLA resin** is a well-documented biodegradable polymer (Tokiwa & Calabia, 2006) that reduces environmental impact compared to non-biodegradable resins like epoxy.

Additionally, the decreased reliance on carbon fiber contributes to a **20% reduction in carbon dioxide emissions** during production. This reduction is attributed to the lower energy requirements of Flax fibers and PLA resin compared to carbon fiber manufacturing, which produces approximately **20 tons of CO_2 per ton of fiber** (Prenzel et al., 2024).

4. Durability and Sustainability Balance

The proposed composite achieves a balance between mechanical performance and sustainability:

- The **mechanical strength** is sufficient to withstand the demands of high-intensity field hockey play, providing durability and reliability under stress.
- The **sustainability improvements**, including reduced carbon emissions and increased biodegradability, position the material as an environmentally responsible alternative for hockey stick manufacturing.

IV. DISCUSSION

This study provides a significant step forward in the development of environmentally sustainable materials for hockey stick manufacturing by proposing a novel composite consisting of flax and carbon fibers reinforced in a biodegradable PLA matrix. The tensile testing simulation demonstrated the composite's ability to meet the rigorous mechanical demands of field and ice hockey sticks while enhancing sustainability.

The proposed composite exhibited a tensile strength of **3.738 GPa** and a tensile modulus of **123 GPa**, comparable to traditional carbon fiber/epoxy composites currently used in hockey sticks. The stress analysis confirmed the material's ability to withstand forces up to **36 MPa**, with a minimal deformation of **0.9 mm**, highlighting its durability and suitability for high-performance sports equipment.

In comparison to prior research that used flax fibers in hockey sticks, this study stands out for its in-depth simulation-based validation. By incorporating tensile and deformation analyses, it addressed the composite's adaptability to the mechanical property standards required for professional use, bridging the gap between theoretical material proposals and practical applications.

The composite composition—**56% biodegradable materials** (flax fibers and PLA)—offers a significant environmental advantage over traditional carbon fiber/epoxy composites. The reduction of carbon fiber dependency by **20%** contributes to a **substantial decrease in CO2 emissions**, aligning with global sustainability goals. PLA, as a biodegradable polymer, reduces the long-term ecological footprint of the product, and flax fibers further enhance its environmental friendliness due to their natural origin and biodegradability.

When burned or discarded, epoxy resins used in conventional hockey sticks release harmful vapors and contribute to soil and marine pollution. The use of PLA resin as an alternative mitigates these risks and demonstrates a viable path toward sustainable sports equipment manufacturing.

Despite its promising findings, this research was constrained by a lack of funding and access to physical testing facilities, restricting the study to theoretical modeling and simulation-based validation. While the calculations were based on established laws of materials engineering and referenced from credible sources, physical testing of the composite remains necessary to fully confirm its properties under real-world conditions, such as dynamic impact resistance and fatigue over repeated use.

Future work will aim to overcome these limitations through collaboration with industry partners to facilitate prototyping and experimental validation by conducting tensile testing to prove the capability of the composite to withstand real hockey situations and will also be tested through aerobic biodegradation in soil tests to prove it’s aligning with the **ISO 17556** for biodegradability in soil. **Carbon nanotubes** (CNTs) represent an additional area of interest for future research. These nanomaterials are known for their exceptional mechanical properties, such as high tensile strength and modulus while being lightweight. CNTs have also shown biodegradability under certain microbial conditions, making them a potential candidate for further enhancing the composite's strength-to-weight ratio and sustainability. Additionally, the feasibility of recycling flax fiber and PLA composite through thermal or enzymatic degradation methods could be explored to close the material's lifecycle loop.

V. CONCLUSION

This study successfully demonstrates the potential of a **Flax/Carbon fiber-reinforced PLA composite** as an environmentally friendly and mechanically robust alternative to traditional carbon fiber/epoxy composites for hockey sticks. By achieving competitive mechanical properties while incorporating 56% biodegradable materials, the proposed composite balances strength, durability, and sustainability.

Key contributions of this research include:

1. Achieving a **20% reduction in CO2 emissions** through decreased reliance on carbon fibers.
2. Demonstrating **minimal deformation (0.9 mm)** and a tensile strength of **3.738 GPa**, meeting the rigorous demands of field and ice hockey.
3. Pioneering the integration of natural fibers and PLA resin to improve the biodegradability of hockey sticks without compromising performance.

While this research remains theoretical, the findings provide a strong foundation for practical application and further exploration. The adoption of advanced materials such as carbon nanotubes and enzymatic recycling methods in future studies has the potential to enhance both the mechanical performance and environmental sustainability of hockey sticks, positioning this approach as a benchmark for sustainable sports equipment design.

VI. ACKNOWLEDGMENT

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