

Development of a Polar Bear-Inspired Starch Bio-composite Reinforced with Graphene Oxide-Coated Coconut Coir

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1 Introduction

The development of bio-composites has emerged in response to the growing demand for sustainable and high-performance materials. Among the various application areas, thermal insulation and energy conservation have gained significant attention due to their direct implications in environmental sustainability. Over the past decades, advancements in nanotechnology and biomimetic strategies have revolutionized the design and functionality of insulating materials.

The source of inspiration in biomimetic thermal insulation design is polar bear (*Ursus maritimus*). It is an apex predator well adapted to extreme Arctic environments, capable of enduring temperatures as low as -46°C [1]. This exceptional thermal resistance is attributed to a hierarchical natural heat recovery system, composed of a thick fat layer, black skin, and a dual-layer fur structure consisting of ground hair and guard hair. The outer guard hair possesses a hollow, pigment-free core that facilitates the absorption of ultraviolet radiation, subsequently converting it into heat [1]. The hollow microstructure of guard hair traps air and reduce convective heat loss, while the dense shell provides tensile strengths up to 300 MPa with strain values around 35% ensuring durability under harsh conditions [2].

Various synthetic attempts have been made to replicate these functional features. For instance, hollow polyurethane fibers coated with reflective aluminum platelets have demonstrated low mid-infrared (MIR) emissivity and promising insulation performance. Fabricated via coaxial wet spinning, these materials show potential in thermal insulation textiles [3]. These artificial fibers suffer from insufficient mechanical robustness and raise concerns regarding sustainability, which limit their widespread adoption.

To overcome such limitations, ice templating has been introduced as a technique for producing porous fibers with both high mechanical strength and thermal insulation properties. These fibers show promise in multifunctional applications such as electro-heating, solar steam generation, and fire protection [4]. The challenges related to ice growth control and extended

fabrication times must be resolved for practical implementation. The requirement of new fiber development raised with these gaps.

A critical comparison between natural and artificial fibers reveals that natural fibers sourced from plant, animal, or mineral origins offer distinct environmental advantages such as biodegradability, renewability, and low ecological impact [5]. Among available natural fibers, coconut coir emerges as a particularly promising candidate for biomimetic insulation. As a naturally occurring hollow fiber, lightweight, and low-cost demonstrates favourable thermal insulation and elongation properties [6], [7]. Its porous structure makes it suitable for mimicking the internal hollow core of polar bear guard hair. Its hydrophilic nature necessitates surface treatments to minimize moisture uptake [8].

To replicate the polar bear guard hair's outer cortex, the selected natural hollow fiber is coated with a material that has low thermal conductivity and high surface area. Graphene oxide (GO) is an ideal candidate due to its mechanical properties, low electrical conductivity, and functionalize surface chemistry [9]. Derived from graphite through oxidative processes such as the Hummers' method, GO contains oxygenated functional groups that make it suitable for composite development [10]. Despite challenges in controlling oxidation levels and achieving uniform reduction factors that significantly influence thermal behaviour, GO remains a highly versatile material for innovative insulation designs [10].

Cassava starch is selected among various bio-composite matrices due to its superior thermal, mechanical, and eco-friendly properties. It exhibits low thermal conductivity that decreases with increasing temperature and concentration, along with stable gelatinization behaviour between $64-74^{\circ}\text{C}$ and enthalpy around 14.7 J/g [11]. Its strong compatibility with natural fibers enables cohesive, porous structures ideal for thermal insulation [12]. Thermoplastic cassava starch (TPCS) reinforced with coconut fibers shows enhanced tensile and flexural strength due to 19–26% amylose content [13]. Being biodegradable and renewable, cassava starch supports

sustainability, while its ease of hot-press processing further strengthens its selection for this bio-composite.

As the coated fibers alone are not suitable for standalone applications, our proposed approach focuses on the development of a bio-composite material. This composite integrates the GO-coated coir fibers, mimicking the architecture and function of polar bear guard hairs, within a sustainable matrix. The composite is fabricated at laboratory scale, and its performance is evaluated based on thermal conductivity, compressive strength, and durability, using standardized characterization methods. This work contributes toward the advancement of eco-friendly thermal insulation materials, bridging the gap between natural inspiration and engineering application.

2 Materials and Methods

2.1 Preparation of Natural Coconut Fiber

Raw coconut husks were initially collected as the source of natural fiber. The husks were soaked in water for 48 hours to soften and loosen the fibrous content. Then, the husks were thoroughly washed with clean water to remove any adhering dust, debris, or unwanted organic matter. The washed husks were dried under direct sunlight until completely moisture-free. Once dried, the fibers were manually extracted, and neat fibers of appropriate length and diameter were manually picked for further use.

2.2 Graphene Oxide Coating

Graphene oxide (GO) used in this study was procured from Ceylon Graphene Technologies, synthesized from natural graphite and containing a moisture content of 60.9%. Five GO solutions were prepared at concentrations of 0.25 g/L, 0.5 g/L, 1 g/L, 2 g/L, and 4 g/L by dispersing the required amount of GO in distilled water. Natural coconut coir fibers were coated by immersing them three times in each of the prepared GO solutions.

2.3 Bio composite development

As the initial step of bio composite development, 3g of cassava starch powder was dissolved in 20 ml of distilled water. Then, 1.7 mL of glycerin was added as a plasticizer. The mixture was heated on a magnetic stirrer at 400 rpm until reaching 80 °C. While maintaining the temperature and stirring, 1.7 mL of 0.1 mol/dm³ acetic acid was added to enhance gelation. As the mixture thickened, the stirring speed was increased to 800 rpm

and maintained for 10 minutes. Once the solution turned transparent, it was poured into a petri dish and evenly levelled using a spatula. The petri dish was then placed in an oven at 50 °C for 24 hours. After drying, the formed starch film was carefully removed.

After preparing the starch film, the composite fabrication process was initiated. This involved placing the coconut coir on top of the starch film within the petri dish prior to the drying stage. To ensure better integration and avoid premature thermal effects, the starch film was allowed to cool at room temperature for 4–5 minutes before adding the coir. This step was particularly critical when using graphene oxide-coated coir, as elevated temperatures could lead to the reduction of graphene oxide, potentially altering its properties. Using this procedure, all three types of composites were successfully prepared. A schematic diagram on the steps followed in bio composite development is shown in **Fig. 1**.

2.4 Characterization

For morphological analysis, both non-coated and GO-coated coir samples were examined using Scanning Electron Microscopy (SEM). Sharp cross-sections required for SEM imaging were prepared by fracturing the fibers in liquid nitrogen, preserving structural integrity. The suitability and chemical structure of the GO were confirmed via Fourier Transform Infrared Spectroscopy (FTIR). In thermal conductivity tests, two highly polished copper plates are employed as the conduction surfaces. The lower plate is fitted with an embedded resistive heater, which elevates and maintains its temperature at a predetermined set-point. The bio-composite specimen is placed directly at the top of this heated plate, and a second, identical copper plate rests on the specimen's upper face; this upper plate houses a precision temperature sensor that continuously monitors the specimen's top-surface temperature. Once the system reaches a steady state, where the heat flux through the composite is constant, the temperature difference between the lower (heated) plate and the upper (sensor) plate is recorded. Under these conditions, the thermal conductivity k is given by,

$$k = \frac{P \times D}{A \times \Delta T}$$

Where, P is the steady-state power supplied to the heater, D is the thickness of the composite specimen, A is the cross-sectional contact area between the specimen and

each copper plate, and ΔT is the temperature difference between the two plates.

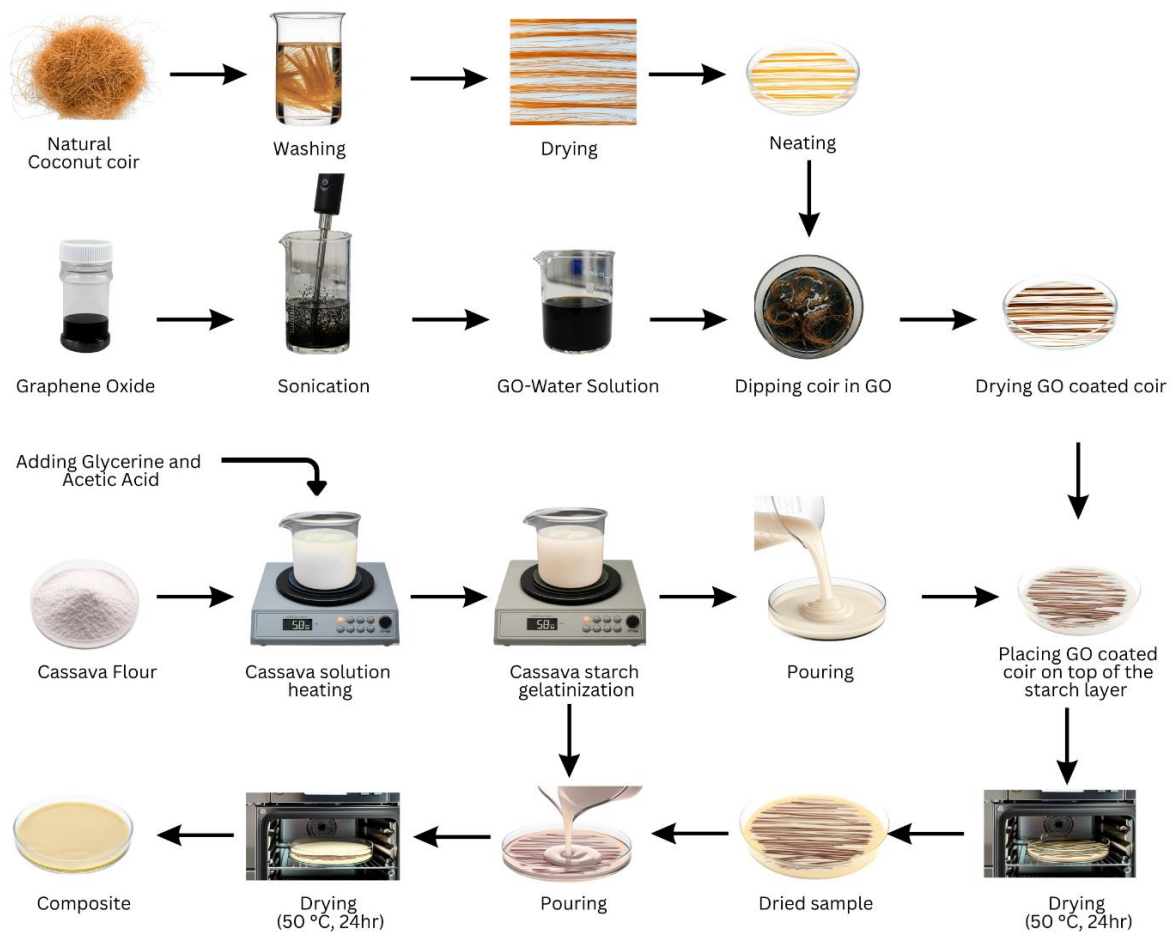


Figure 1. Composite preparation methodology.

3 Results and Discussion

3.1 Coated fibres

The GO-coated coconut coir samples exhibited visible surface changes compared to the uncoated fibres (**Fig. 2**). Moreover, SEM analysis confirmed filled micro voids and smooth fiber surface.

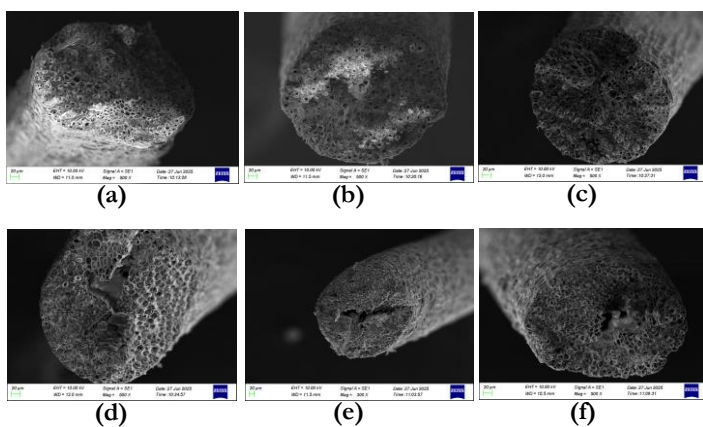


Figure 2: (a) Non-Coated Coir (b) 0.25g/l GO Coated Coir (c) 0.5g/l GO Coated Coir (d) 1g/l GO Coated Coir (e) 2g/l GO Coated Coir (f) 4g/l GO Coated.

According to previous studies, an optimal GO concentration of 0.56 g/L has been reported [14]. In this work, higher concentrations were tested to evaluate whether increased GO loading would enhance coating thickness or improve adhesion. No such improvements were evident from the visual SEM observations. Therefore, subsequent sample preparation was carried out using a GO concentration of 0.5 g/L.

3.2 FTIR Analysis

The FTIR spectra were analysed to verify the successful integration of the constituent materials (**Fig. 3**). The analysis confirmed a successful surface coating of GO onto coir and its subsequent layering with starch. The results showed enhanced physical blending within the composite structure, indicating good adhesion and integration. This physical interaction is crucial for maintaining the individual properties of each component while achieving synergistic performance.

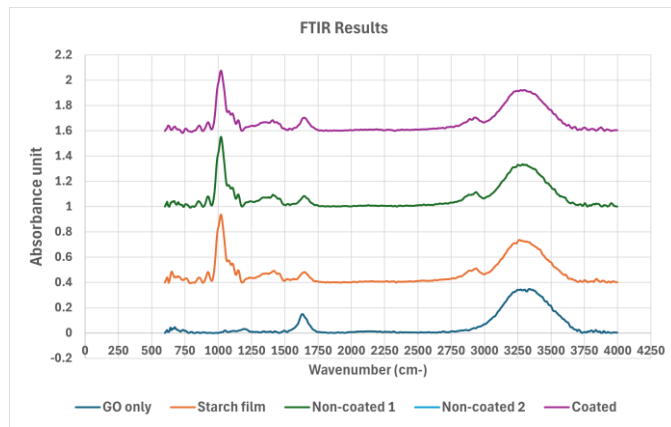


Figure 3: FTIR Analysis of GO, Starch, Non-coated coir, and Coated coir samples.

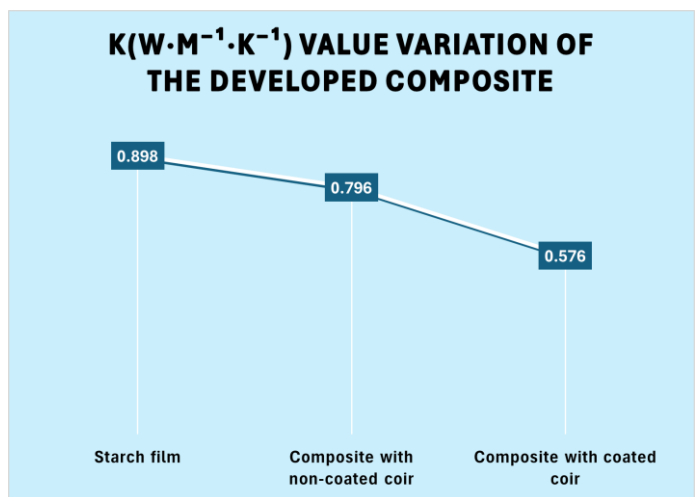
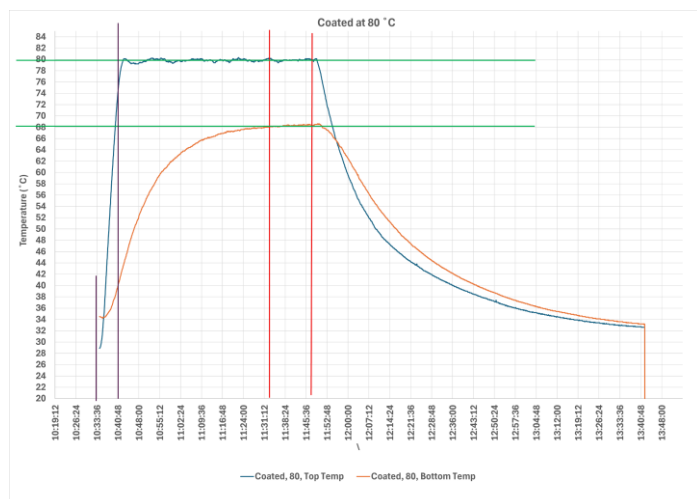
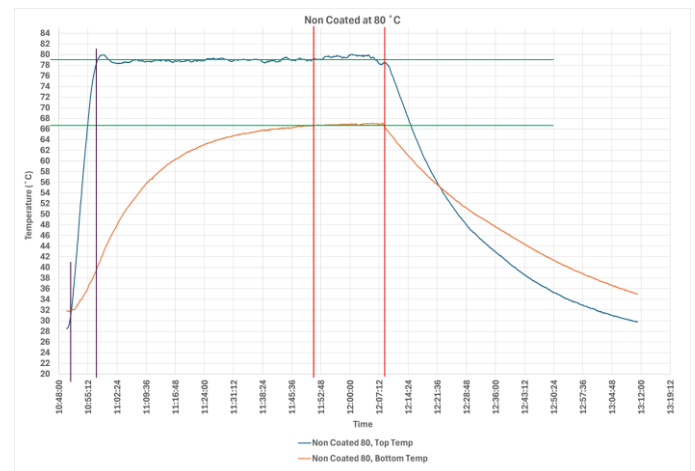
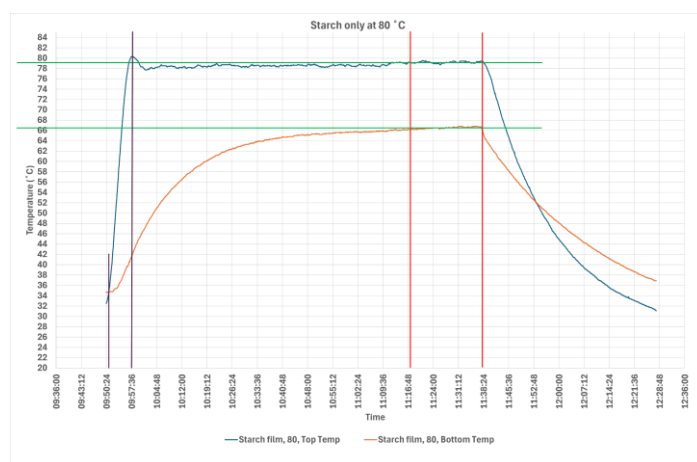


Figure 4. Thermal conductivity results graphs and comparison of Starch film, Composite with non-coated coir, and Composite with coated coir.

4 Conclusions

This research successfully developed a novel bio-composite inspired by the structure of polar bear fur, demonstrating strong potential as a sustainable material for thermal insulation. The incorporation of GO-coated coconut coir into a starch matrix significantly improves

3.3 Thermal Conductivity Test

The primary goal of this research was to enhance the thermal insulation of the bio-composites, and the thermal conductivity tests confirmed the success of the material design (**Fig. 4**). The incorporation of GO-coated coir fibers into the starch matrix resulted in a significant reduction in thermal conductivity. The value decreased from 0.898 W/m·K for the starch-only sample to 0.576 W/m·K for the GO-coated coir composite. This represents a performance improvement of over 35%, clearly demonstrating the effectiveness of the bio-inspired hollow fiber design in impeding the heat transfer.

used. Since the outer layer is consisting of starch, this can't be withstood more than 150 °C as tested. These causes limit the range of applications.

The composite material is a promising candidate where sustainability comes into the picture such as green building materials. Future work should focus on optimizing fiber alignment and exploring advanced surface treatments to further enhanced performance. Finding ways to overcome the above limitations pave the way for more research. Refining the fabrication process will be essential for scaling up production for industrial applications.

Declaration of Competing Interest

The authors declare no competing interests.

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Keywords

Cassava starch, Coconut coir, Graphene oxide, Bio-composite, Thermal insulation, Sustainability.

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