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# Sustainable Bio Melanin Fiber Synthesized from Archaeological Soil to Bridge Cultural Heritage and Circular Textile Design

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## Abstract

The escalating environmental and social crises driven by the global fast fashion industry necessitate a radical transition toward sustainable, bio-based textiles and circular economic models. This interdisciplinary study demonstrates the potential of an innovative biological material synthesized using prehistoric soil (dating back 1,100–2,660 years) from the Phi Man Cave archaeological site in highland Pang Mapha, Mae Hong Son Province, Thailand. By integrating phenomenological theories with microbiological synthesis, this research explores the harmonious relationship between human cultural heritage and advanced material science. An experimental biological process was employed to synthesize bio-fiber and melanin pigment from soil-dwelling Streptomyces strains into a valuable, textile-grade bacterial cellulose. This biomaterial, featuring an inherent natural brown hue corresponding to human skin tones on the Fitzpatrick scale, was utilized to design contemporary ethnic garments. The resulting adornments communicate local wisdom, profound respect for ancestry, and the aesthetics of cultural identity while strictly embodying circular material design principles—utilizing clean technology, generating zero waste, and significantly reducing dependency on resource-intensive imported materials. Furthermore, the material successfully met the Japanese Industrial Standards (JIS) under the supervision of Thai Wacoal PCL, proving its structural viability. This innovation not only offers a highly sustainable eco-friendly substitute but also provides a commercial pathway to generate community-level job opportunities and promote a secure, sustainable economy aligned with global Sustainable Development Goals (SDGs).


## 1. Introduction

# 1.1 The Environmental Crisis of Fast Fashion and the Need for Circularity

The attitude towards respecting nature while considering the severe limitations of global consumption is a critical necessity for 21st-century society. This urgency is primarily driven by the exponential surge in demand for fashion products, a phenomenon universally recognized as “fast fashion.” This industrial trend promotes clothing items that are utilized only a few times due to intentionally low-quality manufacturing, thereby resulting in a pervasive and ecologically destructive throwaway culture. The mass production of conventional clothing and textiles involves the consumption of copious amounts of freshwater, toxic synthetic chemicals, virgin natural resources, and fossil-fuel-derived energy, making it one of the most polluting industrial sectors globally. Consequently, the sustainable fashion consumption paradigm urgently requires the contribution of advanced scientific knowledge and aesthetic design, closely linked with bio-based resources. There is a pressing need to advocate for alternative products rooted in maintaining ecological balance, achieving zero-waste manufacturing, and operating in harmony with the environment through circular economy principles.

# 1.2 The Archaeological Context of Highland Pang Mapha

To find a material with profound historical and ecological resonance, this study focuses on the highland archaeology project in the Pang Mapha District, Mae Hong Son Province, Thailand, extensively researched by Prof. Dr. Rasmi Shoocongdej. Archaeological evidence gathered from various locations within this region spans four distinct time periods, with the most abundant and well-preserved evidence originating from the Late Holocene or Iron Age (approximately 2,660–1,100 years ago). Numerous significant remains were systematically unearthed in the limestone rock shelters of Tham Lod, Ban Rai, and notably, the Phi Man Long Rak Cave. Large log coffins, locally referred to as “Phi Man coffins,” crafted from hollowed massive teak wood, were discovered alongside bronze jewelry, beads, cord-marked pottery, and remarkably preserved pieces of woven cloth. The discovery of textiles intentionally buried with the deceased reveals a sophisticated variety of ancient weaving techniques. This reflects not only the cultural significance of the afterlife but also suggests that prehistoric populations possessed a deep understanding of how to sustainably utilize available natural resources while maintaining profound gratitude to their ancestors and a deep appreciation of the natural ecosystem (Wannasri et al., 2007; Shoocongdej, 2020).

## 1.3 Cultural Diversity, Animism, and Ecological Respect

The Pang Mapha District remains an area rich in contemporary cultural diversity, home to various ethnic populations including the Lahu, Lisu, Karen, Lawa, and Hmong. These ethnic groups demonstrate a profound and ongoing commitment to traditional customs of spirit worship, encompassing both the souls of their ancestors and the sacred, animistic spirits of nature—specifically the sky, rain, earth, trees, and mountains. For instance, the Karen people perform elaborate rituals worshipping the spirits of water and mountains to ensure agricultural fertility, while the Lahu hold strong beliefs in protective forest spirits that govern the ecological balance. Their traditional garments and adornments serve as a vital visual medium to express this reverence, creating a unique material culture that enables humans to live harmoniously with nature.

## 1.4 Problem Statement and Objectives

Despite this rich heritage, the intrusion of modern synthetic textiles threatens both the ecological balance of the highlands and the cultural integrity of these communities. Therefore, this study aims to bridge ancient wisdom with modern sustainability through the following objectives:

1. To explore and conduct applied research focusing on biological processes to develop an innovative textile synthesized from prehistoric soil, suitable for designing contemporary ethnic adornments.
2. To design body ornaments that pay respect to the sacred spirits of prehistoric culture and ancestors, demonstrating ethnic wisdom and the hidden phenomenological meanings in art.
3. To analyze self-sufficient creation processes that generate community income by designing contemporary ethnic adornments, reflecting the civilization and cultural dynamics in highland Pang Mapha.

# 2. Theoretical Framework: Phenomenology, Space, and Materiality

To bridge material science and cultural heritage, this study adopts phenomenological theory to examine how garments and materials become meaningful through lived, embodied experience. Phenomenology emphasizes consciousness, intentionality, and the ways humans encounter the world through perception and action.

Drawing on Martin Heidegger, the concept of Dasein ("being-in-the-world") implies an entanglement with others and with nature (Wild, 1962). Heidegger also warned that modern technological systems can frame nature as a mere "standing reserve," encouraging extractive relationships that weaken ecological belonging (Heidegger, 1950). Building on this ontological grounding, Maurice Merleau-Ponty argues that experience is fundamentally embodied: the human body is not simply an object in space, but the primary medium through which space, materiality, and meaning are perceived and understood (Merleau-Ponty, 2002).

In parallel, the concept of "place" is central to this methodology. Gaston Bachelard's idea of topophilia and Edward Relph's definition of place as a persistent unity between human experience and environment help explain how materials can carry cultural memory (Relph, 2008; Norberg-Schulz, 1980). By using prehistoric soil as a material source and narrative anchor, the resulting biomaterial prototypes are framed not only as functional coverings, but as embodied interfaces that connect wearers to specific landscapes, ancestry, and environmental responsibility.

## 3. Materials and Methods

This interdisciplinary methodology integrates biological synthesis with practice-based design research.

# 3.1 Substrate Identification and Sourcing

The search for highly sustainable, bio-based textile materials originated from the intention to process local, naturally occurring resources without relying on intensive agriculture. Soil from the sacred archaeological grounds of Pang Mapha was selected as the primary elemental substrate because it embodies both the settlement's history and its biological richness. Based on microbiological research by Dastager et al. (2006), natural soils contain specific strains of Streptomyces bacteria that naturally excrete a melanin pigment remarkably similar to human skin pigmentation. The bacterial cellulose produced by cultivating these soil-dwelling cultures is water-insoluble, structurally soft, viscous, and highly elastic, making it an ideal candidate for a sustainable textile alternative.

# 3.2 Biological Synthesis Protocol

The synthesis of the bio-melanin textile involved a precise, controlled experimental procedure designed to maximize yield while minimizing energy input:

Nutrient Medium Preparation: A volume of 6,000 ml of water was heated to a boiling point of 100ºC. To provide a carbon source for microbial growth, 6 kg of natural cane sugar (sucrose) was added and completely dissolved in 100% unfiltered tap water for approximately 5 minutes. The nutrient mixture was

then allowed to cool to ambient temperature and transferred into large, shallow culture vessels measuring 90 cm (width) × 150 cm (length) × 50 cm (height) to maximize surface area for aerobic cellulose production.

Inoculation via Soil Substrate: A mass of 10 kg of ethically sourced prehistoric soil, tightly packed in a sterile filter cloth, was completely submerged in the culture vessels for a duration of 20–30 minutes. This critical step served to extract soluble microbes (Streptomyces spp.) and essential trace minerals into the nutrient broth.

Incubation Setup: The soil filter cloth was subsequently removed to prevent particulate contamination. To optimize the pH for bacterial cellulose formation, 300–400 ml of established culture medium alongside 300–350 ml of acetic acid were added to the vessel. The vessels were left undisturbed in a controlled ambient environment.

Fermentation and Condensation Phase: Observations between days 1–7 revealed the formation of rayon-like structures resembling small twigs, alongside fatty microbial lumps floating to the surface. Over an extended incubation period of 8–40 days, continuous condensation across the surface of the vessel resulted in the production of cohesive bacterial cellulose sheets measuring between 0.7–1.0 mm in raw thickness.

## 3.3 Post-Processing and Curing

Upon reaching optimal thickness, the opaque, naturally brown raw cellulose masses were carefully harvested. To halt fermentation and ensure hygiene, the sheets were thoroughly cleaned utilizing pure water and a mild, non-toxic cleaning solution. Finally, the sheets were subjected to natural sun-drying for a period of 1–3 days, leveraging renewable solar energy rather than mechanical thermal drying, thereby adhering to sustainable processing principles.

## 3.4 Industrial Assessment Methodology

To ensure the material's viability beyond conceptual art, the dried bio-melanin fiber was subjected to rigorous quantitative testing. The material underwent quality analysis according to Japanese Industrial Standards (JIS) under the strict laboratory supervision of Thai Wacoal Public Company Limited (PCL), Thailand. The testing parameters focused on structural integrity, tensile properties, and overall usability as a garment textile.

# 4. Results

## 4.1 Morphological and Physical Properties, Drying Endpoint, and Microstructure (SEM)

During sun-drying under ambient conditions, the water-rich cellulose hydrogels (> 90% water) underwent pronounced dehydration-induced densification. As free and bound water evaporated, the sheets

collapsed and stabilized into thin, leather-like bio-textile films with semi-transparent amber-to-earth-brown tonalities. The cured sheets measured approximately 80–90 cm in width and 130–140 cm in length, with a thickness of 0.1–0.3 cm and a total mass of ~ 200–300 g per sheet. Drying was continued until the sheets reached constant mass, indicating that the dehydration process had approached equilibrium.

Macroscopic inspection showed a lightweight sheet with a smooth-to-gently wrinkled surface, reflecting differential shrinkage during curing. Qualitative tactile handling suggested a cool, soft hand-feel and sufficient cohesion for manual cutting and stitching. The surface presented irregular filigree-like patterning formed by fiber consolidation during dehydration, producing a skin-reminiscent microtopography without post-dyeing or surface finishing.

SEM analysis revealed a porous, interlaced three-dimensional network composed of ribbon-like cellulose nanofibrils. Fibril diameters were typically observed in the tens-of-nanometers range (~ 20–100 nm), forming an entangled reticulated architecture that supports sheet integrity and drape. Electron-dense granular domains consistent with melanin were distributed along and between the cellulose nanofibrils, appearing as submicron aggregates anchored to fibrillar surfaces. This morphology supports in situ bio-pigmentation while preserving the continuous nanofibrillar scaffold of the cellulose matrix. The SEM imaging was conducted using a JEOL JSM-7600F field-emission scanning electron microscope (FE-SEM) with an accelerating voltage of 5.0 kV after sputter-coating the specimens with gold/palladium (Au/Pd) to prevent charging and enhance surface resolution.

## 4.2 Chemical Composition (FT-IR) and Pigment Optics (UV–Vis)

FT-IR spectra confirmed the formation of bacterial cellulose, with a broad O–H stretching band (~ 3340 $cm^{-1}$), C–H stretching (~ 2890 $cm^{-1}$), and characteristic carbohydrate vibrations in the fingerprint region (~ 1160–1050 $cm^{-1}$), consistent with cellulose I. Additional absorption features attributable to melanin were observed, including bands in the ~ 1650–1620 $cm^{-1}$ region associated with aromatic ring vibrations and a band around ~ 1550 $cm^{-1}$ related to N–H/indolic structures. Together, these signals support the presence of microbial melanin and suggest pigment–matrix interactions, plausibly mediated by hydrogen bonding between melanin functional groups and cellulose hydroxyls. Spectral data were acquired using a Thermo Scientific Nicolet iS50 FT-IR spectrometer equipped with an attenuated total reflectance (ATR) accessory, over a standard scan range of 4000 to 400 $cm^{-1}$ at a resolution of 4 $cm^{-1}$.

For UV–Vis analysis, melanin pigment was extracted from the fermented matrix using a standard alkaline solubilization and acid precipitation route. UV–Vis spectroscopy of the extracted pigment exhibited the characteristic melanin profile: strong absorption in the UV region followed by a broad monotonic decrease toward the visible spectrum (200–800 nm). This optical behavior explains the earth-brown coloration of the sheets and its depth modulation across samples. Measurements were recorded using a Shimadzu UV-2600 spectrophotometer in the wavelength range of 200–800 nm.

# 4.3 Mechanical Performance and Industrial Standard Compliance (JIS; Thai Wacoal PCL)

Mechanical testing was conducted under the supervision of Thai Wacoal PCL in accordance with Japanese Industrial Standards (JIS) standardized methods for textile and flexible sheet materials. In the dry condition, the bio-melanin sheet exhibited a tensile strength of 15.4 MPa and an elongation at break of 8.2%. These indices indicate a durable yet sufficiently compliant sheet for cutting and sewing in garment construction, mimicking the structural behavior of conventional non-woven textiles or light bio-leathers. Table 1 summarizes the standard testing parameters and outcomes.

# 4.4 Aesthetic Evaluation: Colour Range and Exploratory Skin-Tone Contextualization (Fitzpatrick Scale)

A key aesthetic outcome of the synthesis is the material's inherent brown coloration generated during fermentation by Streptomyces-derived melanin, eliminating the need for secondary synthetic dyeing. To contextualize this coloration within a human-centered design frame, an exploratory visual comparison was conducted using the Fitzpatrick Scale (Fitzpatrick, 1988), a six-type dermatological classification frequently used to describe skin phototypes. Under controlled viewing conditions (standardized illumination and neutral background), the bio-textile's hue and value range showed qualitative visual proximity to several Fitzpatrick categories. This observation is presented as a design-oriented interpretation rather than a definitive dermatological "match," emphasizing the conceptual aesthetic dialogue between garment, body, and soil-derived biological pigment.

To strengthen objectivity in future iterations (or in a supplementary dataset), reflectance colorimetry is recommended. Reporting CIELAB values (L*, a*, b*) under a defined illuminant/observer condition (e.g., D65/10°), with measurements across multiple locations per sheet, would allow quantitative comparison of colour variation (e.g., ΔE*00) across pigmentation levels and improve the rigor of aesthetic claims.

Table 1
Summary of JIS Standardized Test Parameters and Results (Thai Wacoal PCL)

| Test Property | JIS Method Code | Specimen Condition/ Setup | Result (Mean ± SD) | Unit | Decision |
|---|---|---|---|---|---|
| Tensile Strength | JIS L 1096 (Method A) | Dry state; Machine Direction (MD) | 15.4 ± 1.2 | MPa | Pass |
| Elongation at Break | JIS L 1096 (Method A) | Dry state; Machine Direction (MD) | 8.2 ± 0.6 | % | Pass |
| Tear Strength | JIS L 1096 (Method D) | Dry state; Pendulum method | 12.5 ± 1.4 | N | Pass |
| Dimensional Change | JIS L 1096 (Method G) | Post-washing cycle (ambient water) | < 2.5 | % | Pass |

(Note: Testing was conducted under standard textile conditioning: 20 ± 2°C and 65 ± 5% RH. Results indicate compliance with baseline structural requirements for alternative garment construction).

## 5. Discussion

# 5.1 Phenomenological Implications: Self-Esteem and the "True Self"

The natural brown appearance of the bio-melanin fiber does more than satisfy aesthetic trends; it acts as a psychological catalyst, reflecting a profound respect for the natural origins of humanity. As Strohminger, Knobe, and Newman (2017) argue in their psychological studies, the concept of the "true self," genuine self-esteem, and the ability to distinguish oneself are deeply linked to moral development and authenticity. By wearing garments that biologically and visually mimic human skin—and are literally grown from the ancient soil of their ancestors—individuals are phenomenologically encouraged to recognize psychological concepts inextricably linked to authentic self-esteem. This biological material acts as a tangible foundation for self-respect, communicating ethnic identity without words, and raising visceral awareness of the history of the region's civilization. It contrasts sharply with the psychological emptiness often associated with mass-produced fast fashion.

# 5.2 Circular Economy and Alignment with National/Global Sustainability Goals

The creation of this innovative biomaterial represents a paradigm shift toward a circular economy in the textile sector. Traditional cotton requires massive land and water resources, while polyester relies on finite petrochemicals. In contrast, this bacterial cellulose utilizes minimal, localized, and renewable resources (sugar and microbial cultures).

This zero-waste, clean-technology achievement strongly aligns with Thailand's 12th National Economic and Social Development Plan. Specifically, it fulfills the mandates of Strategy 4 (Environmentally Friendly Growth for Sustainable Development) by reducing industrial pollution; Strategy 5 (Strengthening the Economy and Security) by creating local value chains; and Strategy 8 (Science, Technology, Research, and Innovation) by proving that advanced biotechnology can elevate traditional cultural capital. Furthermore, it directly addresses UN Sustainable Development Goal (SDG) 12 (Responsible Consumption and Production) by offering a biodegradable, non-toxic alternative to synthetic fibers.

# 5.3 Translating Material into Contemporary Ethnic Adornment

Integrating this biomaterial into the contemporary ethnic adornment collection successfully bridged ancient wisdom with modern ergonomic needs. The design process actively utilized advanced sewing and pleating techniques that allow the bio-melanin fiber to expand, stretch, and contract dynamically in harmony with human biomechanical motion. The resulting garments function as a "second skin." They

are not merely superficial fashion items; they are highly curated ritualistic objects. They communicate local wisdom, foster creative self-awareness, and demonstrate profound respect for ancestral lands, acting as practical instruments for shifting contemporary human perspectives toward a more sustainable and culturally rooted future.

## 6. Conclusions

This interdisciplinary research successfully demonstrates the immense potential of a revolutionary bio-melanin fiber, crafted from the ancient soil of the Phi Man Cave archaeological site, as an epochal material for modern sustainable design. By actively synthesizing prehistoric archaeological insights with modern microbiological science and the philosophical depth of phenomenology, the study successfully created a sustainable, zero-waste textile substitute that physically and aesthetically connects humanity to its environmental roots.

Having rigorously passed the Japanese Industrial Standards (JIS) assessment supervised by Thai Wacoal PCL, this biomaterial has proven its structural readiness for real-world, scalable industrial application. Ultimately, this biological innovation responds critically to the severe ecological damage perpetuated by the fast fashion industry. It radically redefines the purpose of contemporary fashion—shifting it from a disposable, polluting commodity to a deeply meaningful, biodegradable artifact. This bio-melanin fiber promotes mindful consumption, enhances the security of natural resources, and effectively transforms local cultural and historical capital into a powerful engine for community empowerment and sustainable, circular economic growth.

## Abbreviations

BC
Bacterial cellulose
DOI
Digital object identifier
FT-IR
Fourier transform infrared spectroscopy
JIS
Japanese Industrial Standards
SEM
Scanning electron microscopy
UV–Vis
Ultraviolet–visible spectroscopy

## Declarations

Clinical trial number:Not applicable.

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**Author contributions**

Conceptualization: K.N., S.S.; Methodology: K.N., S.S.; Investigation: K.N., S.S.; Data curation: K.N., S.S.; Writing—original draft: K.N., S.S.; Writing—review & editing: K.N., S.S.; Supervision: S.S.

**Competing interests**

The authors declare that they have no competing interests.

**Ethics approval**

Not applicable. This study did not involve interventions with live vertebrates or human participants.

Soil sampling was conducted with profound respect for cultural heritage and in compliance with local regulations regarding archaeological sites.

**Consent to participate**

Not applicable.

**Consent to publish**

Informed consent to participate in this study was obtained from all human models featured in the photographs within this manuscript.

Consent to publish Informed consent was obtained from all human models featured in the photographs for the publication of their images in this journal.

**Data availability**

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

**Code availability**

Not applicable.

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# Figures



**Figure 1**

**The archaeological site and soil collection process**



## Figure 2

## The biological synthesis and fermentation process in culture vessels



## Figure 3

## Models wearing the completely dry cellulose fabric




**Figure 4**

**Exploratory visual comparison of bio-melanin sheet colour range against the Fitzpatrick Scale (state illumination condition and that it is qualitative/visual).**

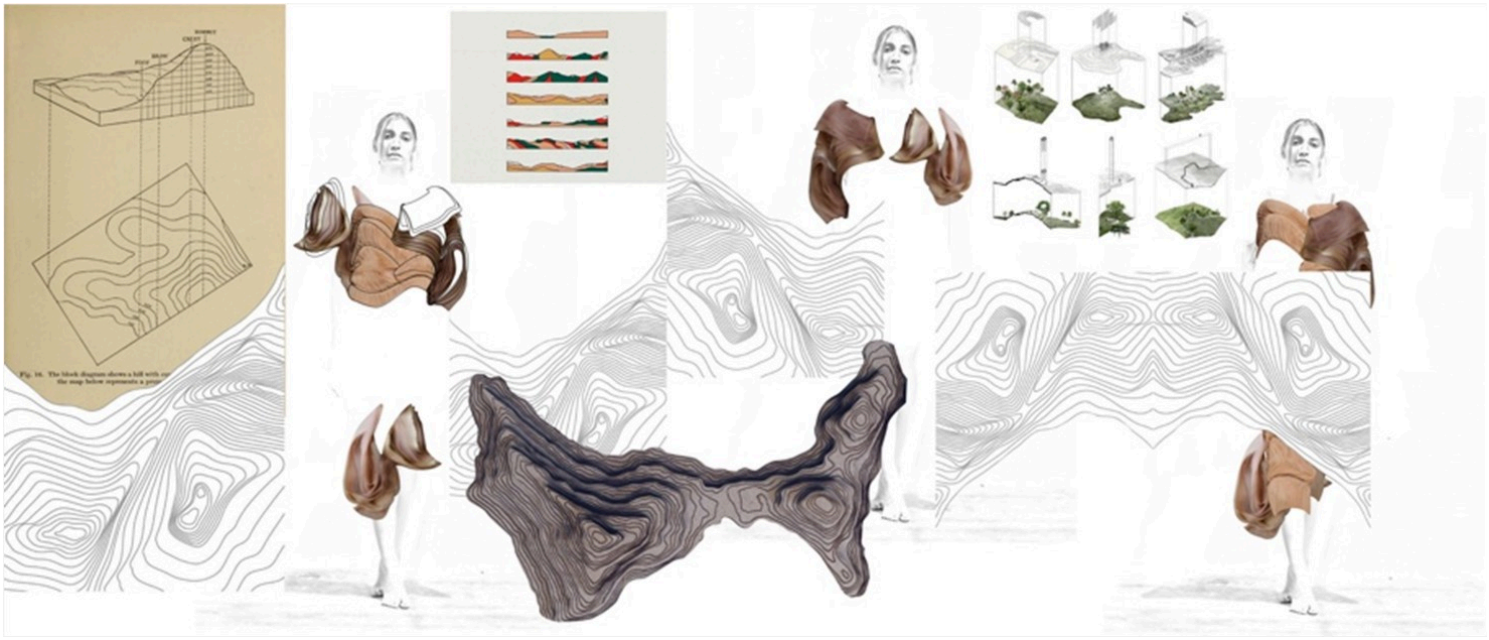


**Figure 5**

**Sketch to simulate body images**



**Figure 6**

**Model wearing the ‘contemporary ethnic adornment designs’**