Woven Biocomposites from Pineapple Leaf Fiber and Orange Peel Waste: A Material Innovation for Sustainable Textiles

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ABSTRAK

Penelitian ini mengembangkan material tekstil biokomposit berbasis tenun dengan memanfaatkan serat daun nanas (PLF) dan bioplastik dari limbah kulit jeruk sebagai bahan pengikat alami. Melalui pendekatan desain kerajinan berkelanjutan, material ini dibuat menggunakan teknik tenun tradisional (ATBM) dan formulasi bioplastik ramah lingkungan berbahan gelatin, agar, gliserol, dan pektin dari kulit jeruk. Penelitian ini mengkaji pengaruh struktur tenun (polos dan keper) dan komposisi serat terhadap sifat mekanik material, khususnya kekuatan tarik dan kelenturan. Hasil menunjukkan bahwa struktur tenun dan kadar serat sangat berpengaruh terhadap performa mekanik. Tenun polos menghasilkan kekuatan tarik lebih tinggi, sementara tenun keper memberikan fleksibilitas dan kenyamanan sentuhan lebih baik. Formulasi bioplastik berperan sebagai pengikat alami yang menyatukan antar serat serta meningkatkan kelenturan material. Biokomposit ini menunjukkan potensi tinggi sebagai solusi material tekstil berkelanjutan untuk produk kerajinan seperti aksesori, produk interior, dan fashion ramah lingkungan.

Kata Kunci: Bioplastik, Serat Daun Nanas, Limbah Kulit Jeruk, Tenun, Tekstil Berkelanjutan

ABSTRACT

The growing urgency of sustainability in the textile industry necessitates the development of biodegradable materials derived from organic waste. This study introduces a composite material that integrates pineapple leaf fiber (PLF) with bioplastic made from orange peel waste, following the Material Driven Design (MDD) framework. The composite is produced through traditional weaving techniques (plain and twill) and cast using a gelatin–agar bioplastic matrix. Mechanical testing demonstrates tensile strength of up to 26.79 kg and elongation of 98.31%, depending on the PLF content and bioplastic thickness. User perception analysis indicates that samples combining twill weave with 300 ml of bioplastic provide the most desirable tactile and visual qualities. The resulting materials are biodegradable, locally sourced, and aesthetically engaging, positioning them as viable alternatives for accessories and interior products. This research contributes to sustainable material innovation by merging craft traditions with contemporary material experimentation.

Keywords: *Bioplastic, Pineapple Leaf Fiber, Orange Peel Waste, Sustainable Textile, Weaving*

1. Introduction

This study presents the development and characterization of a composite textile material composed of pineapple leaf fiber (PLF) and bioplastic synthesized from orange peel waste, two underutilized agricultural by-products sourced from Subang Regency, West Java, Indonesia. PLF offers high tensile strength, low density, and a natural sheen, making it a strong candidate as a bio-fiber reinforcement (Sgriccia et al., 2008). Meanwhile, orange peel, rich in cellulose, pectin, and limonene, provides a biodegradable polymer matrix with natural adhesive and elastic properties (El-Mekkawy et al., 2019).

The research aims to fabricate a fiber-reinforced composite by integrating pineapple leaf fiber (PLF) woven textiles with orange peel-derived bioplastic, focusing on enhancing mechanical performance (e.g., tensile strength and elongation) while maintaining favorable sensory characteristics such as surface texture, coloration, and olfactory cues. The Material Driven Design (MDD) framework (Karana et al., 2015) is employed to guide material selection and application development through an exploration of sensory, functional, and emotional qualities. Biophilic design principles are also applied to support multisensory engagement and natural aesthetics.

Recent studies support the growing relevance of agricultural waste-based composites in the pursuit of sustainable material innovation. For instance, woven PLF has been shown to significantly enhance the tensile and flexural strength of polymer composites, demonstrating how fiber layering and orientation improve structural performance (Hadi et al., 2022). Similarly, research on *green composites made of polyhydroxybutyrate and long-chain fatty acid esterified microcrystalline cellulose from pineapple leaf* reveals improved interfacial compatibility and biodegradability, underscoring PLF's potential in biopolymer reinforcement (Li et al., 2023). In parallel, orange peel waste has been identified as a promising raw material for vegan leather production due to its high tensile and tear strength, offering valuable insight into the mechanical and aesthetic potential of citrus-based biomaterial (Rimantho, Chaerani, & Sundari, 2024)

By combining traditional hand-weaving techniques with contemporary biopolymer innovation, this study contributes to a novel pathway for sustainable material development in the textile sector. The findings demonstrate the potential for valorizing agricultural waste into functional, biodegradable composite materials, advancing the discourse in material science for eco-conscious fashion, product design, and craft-based applications.

2. Research Method

2.1. Materials

Pineapple leaf fiber (PLF) was selected for its favorable mechanical and environmental properties, including high tensile strength, low density, and natural luster, positioning it as a competitive alternative to conventional bast fibers such as linen and ramie. The extraction of PLF is environmentally benign, typically performed manually or using biological processes without hazardous chemicals, supporting sustainable textile production. In Indonesia, particularly in Subang Regency, West Java, PLF is abundantly available as a by-product of Smooth Cayenne pineapple cultivation, providing a consistent and high-quality raw material for textile applications. Each pineapple plant yields over 70 leaves, with fiber yield and quality influenced by agronomic factors such as planting density and sunlight exposure. The fibers, which constitute approximately 2.5–3.5% of leaf mass, are primarily composed of cellulose, hemicellulose, lignin, pectin, wax, and trace minerals, contributing to their mechanical performance and biodegradability. PLF is fully biodegradable, with decomposition rates ranging from 45 days to under two years depending on environmental conditions and processing. Prior studies have demonstrated that PLF-based composites can achieve tensile strengths exceeding Indonesian national standards for printing paper (SNI 14-0937-2005), confirming their structural viability for sustainable material applications.

2.2. Fabrication

The bioplastic matrix was formulated using gelatin and agar as biopolymers, with PLF (pineapple leaf fiber) serving as the reinforcing filler. Glycerol was incorporated as a plasticizer to modulate flexibility and mechanical performance. The optimized formulation consisted of 800 ml water, 18 g agar, 16 g gelatin, and 15 ml glycerol. Agar, a hydrophilic polysaccharide derived from red algae, acts as a gelling and film-forming agent, while gelatin contributes to matrix cohesion and flexibility. Glycerol, sourced from plant-based materials, enhances elasticity and surface smoothness.

Additionally, pectin extracted from orange peel was integrated into the matrix to improve film-forming ability, tensile strength, and moisture barrier properties. Orange peel pectin, a complex heteropolysaccharide primarily composed of galacturonic acid units, is characterized by its high methoxyl content and excellent gelation behavior in acidic and sugar-rich environments. Characterization of the extracted pectin was conducted using Fourier Transform Infrared Spectroscopy (FTIR) to confirm functional groups, while its degree of esterification (DE) and galacturonic acid content were determined through titrimetric analysis, indicating suitability for biodegradable polymer applications.

The fabrication process followed an adapted method from Davis (2017): (1) gelatin, agar, glycerol, and pectin were mixed and heated with water to boiling; (2) the hot mixture was poured into molds pre-arranged with PLF; (3) the composite was air-dried for three to six days, depending on thickness and ambient conditions. This method yielded a biocomposite with improved flexibility, biodegradability, and mechanical integrity, suitable for sustainable design applications.

Weaving and Composite Formation

Weaving was performed using a plain weave structure, selected for its simplicity, durability, and suitability for evaluating the mechanical and aesthetic properties of PLF-based textiles. In addition to plain weave, twill weaving techniques were also utilized to explore variations in surface texture, flexibility, and structural behavior. Twill weave, characterized by its diagonal rib pattern, offers enhanced drapability and mechanical strength compared to plain weave, making it a valuable option for textile innovation (Bilisik, 2012; Pickering et al., 2016). Both structures were produced using traditional looms (ATBM) and a hand lay-up method, with variations in PLF concentration (25%, 50%, 75%, and 100%) to assess the influence of fiber content on composite performance. The woven PLF served as the reinforcement phase, while the bioplastic matrix provided cohesion and flexibility. This approach integrates local craft traditions with contemporary material science, supporting circular design and the valorization of agricultural waste.

Bioplastic Composite Characterization

The resulting green composites consisted of a biopolymer matrix (gelatin and agar) reinforced with PLF. The synergistic interaction between the matrix and fiber resulted in materials with enhanced tensile strength, stiffness, and biodegradability. The inclusion of PLF as reinforcement aligns with sustainable design objectives by reducing reliance on petroleum-derived synthetics and maintaining the artisanal qualities of traditional textiles. The final biocomposite exhibited improved mechanical and aesthetic properties, with potential applications in sustainable fashion and interior textiles.

2.3. Mechanical Testing

Mechanical properties were evaluated via tensile strength testing, conducted at the Advanced Textile Laboratory, Politeknik STTT Bandung. Samples with varying PLF concentrations and weave types (plain and twill) were tested using a gauge length of 75 mm and a pulling speed of 300 mm/min. This enabled assessment of the relationship between fiber content, weave structure, and mechanical performance.

2.4. User Perception Study

Additionally, qualitative sensory analysis was performed through semi-structured interviews with 30 respondents (aged 20–30, urban residents, sustainability-oriented). Participants assessed the materials based on tactile, visual, and olfactory impressions, as well as potential product applications and emotional responses. Data were analyzed using thematic coding within the Material Driven Design (MDD) framework, emphasizing user-centered evaluation of material aesthetics and functionality in sustainable design contexts.

Material Driven Design (MDD) is a sustainable design approach that begins with material exploration, positioning materials as central to both the function and form of a product. Unlike conventional methods that focus on shape, MDD encourages designers to develop materials alongside the product itself. This approach combines research through design (Frayling, 1993) and constructive design research (Koskinen et al., 2011), supporting circular economy principles by treating the design process as a form of prototyping.

Ashby and Johnson (2009) emphasize the growing importance of materials in product design, shifting the designer's perspective to ask: *What can this material do?* MDD goes beyond technical properties, focusing on how materials influence user experience. Karana (2014) adds that MDD considers emotional responses, sensory interaction, and cultural meaning. The process includes hands-on prototyping and testing to understand a material's potential and limitations (Niedderer, 2012).

MDD involves four stages:

1. Understanding the material through technical and experiential analysis.
2. Envisioning material experience, including sensory, emotional, and cultural aspects.
3. Applying material experiences by exploring their relevance in design contexts, often through user studies.
4. Developing product concepts based on the findings, including using innovative or sustainable materials.

By integrating aesthetic, functional, and sustainable values, MDD helps create meaningful, eco-conscious products. When combined with Biophilic Design, it fosters deeper connections between people, materials, and nature.

3. Result and Discussion

3.1. Material Composition and Weaving Parameters

The study utilized handwoven pineapple leaf fiber (PLF) textiles fabricated using two distinct weave structures: plain weave and twill weave. Four fiber composition ratios were investigated (100%, 75%, 50%, and 25% PLF) blended with rayon yarn. Rayon was exclusively employed in the warp direction to accommodate technical constraints related to loom operation and to align with traditional artisan weaving practices, where rayon serves as a common base yarn. The rayon yarn used was specified as 80/2, indicating a fine, two-ply yarn suitable for high-resolution weaving. The weaving was performed on a non-mechanical handloom (Alat Tenun Bukan Mesin, ATBM) with a reed width of 46 inches. For the twill weave, a 1/4 twill pattern was implemented to evaluate the influence of weave architecture on material properties.

3.2. Preliminary Material Characterization

Prior to advanced testing, the woven PLF samples underwent manual qualitative assessment focusing on key physical attributes: flexibility, color uniformity, surface texture, and odor profile. These evaluations were conducted in accordance with the Indonesian National Standard (SNI) protocols for textile quality assessment. This preliminary screening ensured that the samples met established baseline criteria for textile materials in terms of handleability and sensory acceptability, thereby validating their suitability for subsequent mechanical and functional testing.

Table 1. Analysis of pineapple leaf fiber weaving

Type of Weave	Fiber Content	Analysis
Plain	100%	It has relatively stiff properties with low flexibility, a slightly coarse texture, and a cream color that is slightly darker compared to other materials. It also has a faint natural scent.
Plain	75%	It has relatively stiff properties with moderate flexibility, a slightly rough texture, and a color that is slightly brighter compared to the 100% pineapple fiber variant.
Plain	50%	It has relatively flexible properties and is easy to fold. The color remains within the same beige color range.
Plain	25%	It has flexible properties and a relatively smooth texture. The resulting color is the brightest among the other plain-woven samples.
Twill	100%	It has relatively stiff properties and is somewhat difficult to fold, with a coarse texture, though not as rough as the 100% plain-woven pineapple fiber sample. The resulting color is ivory white, accompanied by a natural scent.
Twill	75%	It exhibits a relatively stiff characteristic with moderate flexibility. The color is slightly brighter compared to the 100% twill-woven pineapple fiber sample.
Twill	50%	It possesses relatively high flexibility and a generally smooth texture. The resulting color appears close to white.
Twill	25%	It exhibits fairly good flexibility and a generally smooth texture, with the brightest color among all woven samples.

3.3. Fabrication Method

The fabrication of biocomposites in this study involved tailoring the composition of biopolymer matrices reinforced with pineapple leaf fiber (PLF) as a natural filler. Gelatin and agar were selected as the primary matrix polymers due to their complementary film-forming, mechanical, and biodegradable properties. The bioplastic formulation comprised gelatin, agar, glycerin, PLF, and water.

Matrix Components:

- Gelatin: A protein-based biopolymer providing cohesive film formation and flexibility.
- Agar: A hydrophilic polysaccharide extracted from red seaweed, serving as a gelling agent that enhances water retention and structural stability. Agar's strong film-forming and biodegradable characteristics improve the composite's mechanical integrity (Rhim et al., 2010).
- Glycerin: A viscous polyol derived from the fermentation of sugars and vegetable oils, incorporated as a plasticizer to modulate elasticity and surface smoothness. The glycerin concentration critically influences mechanical behavior: lower glycerin content yields stiffer, more brittle films, whereas higher concentrations enhance flexibility and reduce surface roughness (Davis, 2017).

Fabrication Procedure:
The bioplastic synthesis followed an adapted protocol based on Davis (2017):

1. Agar, gelatin, and glycerin were homogeneously mixed in a single container.
2. A defined volume of water was added, and the mixture was heated to boiling under continuous stirring to ensure complete dissolution and uniformity.
3. The hot biopolymer solution was then cast into molds pre-lined with woven PLF mats to form the composite structure.
4. Samples were allowed to air dry under controlled ambient conditions.

Drying Conditions:
Drying time varied between 3 to 6 days, dependent on parameters including solution volume, gelatin and glycerin concentrations, biocomposite thickness, and environmental factors such as temperature and humidity. Optimal drying was essential to achieve desired mechanical properties and dimensional stability (Davis, 2017).

Figure 1. Bioplastic exploration

3.4. Matrix Experiment Results

A systematic investigation was conducted to optimize the matrix-to-filler ratio in the biocomposite formulation, aiming to enhance both mechanical performance and material stability. The study specifically varied gelatin concentration and bioplastic layer thickness while maintaining a consistent mold size of 17 × 24 cm to ensure comparability across samples. These parameters were adjusted to refine the composite’s flexibility, tensile strength, and surface quality, thereby advancing the development of an application-ready sustainable material.

3.5. Final Experiment Analysis

Subsequent experiments further evaluated the influence of gelatin concentration and bioplastic thickness on the mechanical integrity and aesthetic properties of the PLF-reinforced biocomposites. Key findings are summarized as follows:

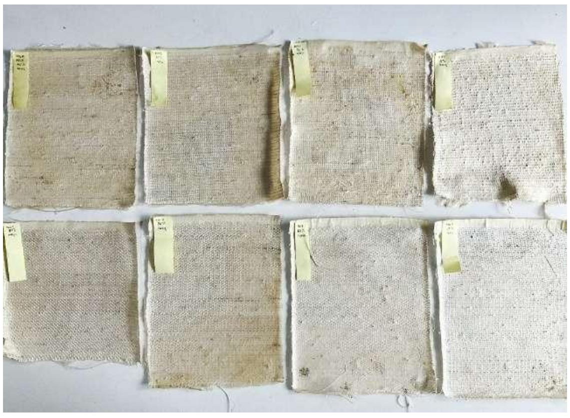

Figure 2. Gelatine exploration

- Gelatin Concentration and Thickness Effects:
  Increasing gelatin concentration by 10% with bioplastic thickness ranging from 0.5 to 1 cm yielded a composite exhibiting improved flexibility and moderate strength. However, surface micro-cracking was observed predominantly over woven PLF regions. This phenomenon is attributed to insufficient matrix thickness relative to gelatin content, which likely impaired polymer chain mobility and hindered optimal interfacial bonding during drying. The samples exhibited a persistent moist odor, possibly due to drying conditions maintained at 35°C and 70% relative humidity. Color variation remained minimal, confined to a cream-to-light brown spectrum.

Figure 3. Thickness exploration

- Thicker Bioplastic Layers (1–2 cm):
  Samples with increased thickness demonstrated smooth, glossy surfaces and maintained flexibility across both plain and twill weave structures. The materials exhibited clean fold lines upon bending and presented a neutral odor profile with consistent cream coloration. However, mold growth was detected in the bottom-left region of a plain weave sample containing 50% PLF, likely caused by localized uneven thickness and elevated humidity, which facilitated microbial proliferation in thicker, poorly ventilated areas.

Figure 4. Dipping method exploration

- Dipping Method Application:
  An alternative fabrication approach involved immersing woven fabrics (twill weave with 25% PLF and plain weave with 75% PLF) into the bioplastic solution followed by drying in predefined shapes.

The resulting composites were rigid, dimensionally stable, and suitable for three-dimensional sculptural applications. Coloration ranged from creamy beige to light brown, and no off-putting odors were detected.

Figure 5. Dehydrator test

- Drying Method Impact:
  Manual sun drying over 3–4 days produced flexible, smooth-surfaced biocomposites with good durability; however, the process was highly weather-dependent, and high ambient humidity increased mold risk. In contrast, machine drying using a dehydrator at 70°C for 10 hours accelerated drying but resulted in stiffer materials with uneven coloration due to limited chamber capacity and non-uniform heat distribution. Samples closer to the heat source exhibited more pronounced browning.

These results demonstrate that bioplastic thickness, gelatin concentration, and drying methodology are critical parameters influencing the mechanical, aesthetic, and microbiological stability of PLF-based biocomposites. Excessive thickness under humid conditions promotes mold growth, while elevated gelatin content without proportional thickness adjustment induces surface cracking. The dipping fabrication method offers promising potential for rigid, form-retaining materials suitable for sculptural or structural applications. Selection of drying protocols must balance processing efficiency with desired material flexibility and surface uniformity.

3.6. Analysis of Drying Methods

The drying process plays a pivotal role in determining the final properties of biocomposites composed of pineapple leaf fiber (PLF) and orange peel-based bioplastic. Two drying techniques were evaluated: manual sun drying and machine drying using a dehydrator. Manual drying under direct sunlight required approximately 3 to 4 days and was highly dependent on environmental factors such as ambient temperature, relative humidity, and airflow. This method yielded biocomposites with favorable flexibility, smooth surfaces, and satisfactory mechanical strength. However, samples with uneven bioplastic thickness exhibited localized mold growth, particularly in regions exposed to high humidity, highlighting a vulnerability to microbial contamination under these conditions.

In contrast, machine drying using a dehydrator set at 70°C for 10 hours significantly reduced drying time and minimized exposure to ambient moisture, improving process efficiency. Despite these advantages, this method presented limitations including restricted batch capacity and uneven heat distribution, which resulted in heterogeneous moisture removal. Consequently, the biocomposite surfaces became stiffer and more brittle, with darker discoloration observed near the heat source, indicative of localized over-drying and thermal gradients within the samples.

The interplay between matrix formulation and bioplastic thickness further influenced drying outcomes. Increasing gelatin concentration by 10% within bioplastic layers of 0.5 to 1 cm thickness improved flexibility but induced surface micro-cracking, likely due to suboptimal polymer-fiber bonding during drying. Thicker bioplastics (1 to 2 cm) exhibited smoother and glossier surfaces but were more susceptible to fungal growth, especially in loosely woven or thick sections, as observed in the 50% PLF plain weave samples. These findings underscore the necessity of balancing formulation parameters with drying conditions to optimize material performance.

An alternative fabrication approach, the dipping method, where woven textiles are immersed in the bioplastic solution and dried in predefined shapes, produced rigid, dimensionally stable composites suitable for three-dimensional applications. These samples demonstrated uniform cream-to-brown coloration and neutral odor profiles, indicating potential for sculptural and structural uses.

These experimental observations align with literature reports emphasizing the critical influence of drying parameters on bioplastic properties. For example, Pongmassangka et al. (2020) demonstrated that drying cornstarch-glucomannan composites at 70°C for 16 hours yielded tensile strengths around 2.4 MPa. Similarly, Simanjuntak (2024) reported that dehumidifier-assisted drying of sweet potato starch films for 22 hours optimized film thickness and reduced water absorption, enhancing overall material quality.

In summary, the drying method, combined with matrix composition and filler distribution, is a decisive factor in achieving biocomposites with balanced mechanical strength, surface integrity, and resistance to microbial growth. Optimizing drying conditions is essential for producing sustainable textile materials that meet stringent functional and aesthetic criteria, thereby advancing their applicability in eco-friendly design and manufacturing.

3.7. Textile Tensile Testing

Tensile strength, defined as the maximum stress a material can withstand under uniaxial tension before failure or significant plastic deformation, is a critical mechanical property for evaluating textile performance (ASM International, 2004). In this study, tensile strength tests were performed at the Advanced Textile Laboratory of Politeknik STTT Bandung on May 7, 2025.

The testing protocol employed a grip distance of 75 mm and a constant crosshead speed of 300 mm/min, consistent with standard textile testing procedures. Samples consisted of handwoven fabrics produced with two weave patterns: plain weave and twill weave. Each fabric variant incorporated pineapple leaf fiber (PLF) at four different concentrations, 25%, 50%, 75%, and 100%, blended with rayon yarn in the warp direction to accommodate weaving constraints.

This experimental design enabled systematic assessment of the effects of PLF content and weave architecture on tensile strength. The results provide insight into the mechanical viability of PLF-based textiles and inform optimization strategies for sustainable fiber blends in textile applications.

Table 2. Tensile strength test results of plain weave fabric

Fiber Content	Tensile Strength (kg)	Elongation (%)
25%	26,79	68,4
50%	24,10	73,51
75%	19,02	78,24
100%	22,19	98,31

There was a decrease in tensile strength as the pineapple fiber composition increased, particularly at the 75% fiber content. However, the elongation value increased, indicating enhanced material elasticity.

Table 3. Tensile strength test results of twill weave fabric

Fiber Content	Tensile Strength (kg)	Elongation (%)
25 %	11,75	65,91
50%	13,65	62,53
75%	13,86	79,20
100%	12,66	70,97

The tensile strength of the handwoven fabrics exhibited a decreasing trend with increasing pineapple leaf fiber (PLF) content, notably at the 75% fiber concentration. This reduction in tensile strength suggests that higher PLF proportions may compromise the load-bearing capacity of the composite textile. Conversely, elongation at break increased with greater fiber content, indicating enhanced material elasticity and flexibility.

These observations reveal an intrinsic trade-off between mechanical strength and ductility within the PLF-reinforced textiles. Elevated fiber content appears to promote stretchability and deformation capacity, potentially due to the natural fiber's morphology and fiber-matrix interactions, but at the expense of tensile resistance. Understanding this balance is critical for tailoring PLF-based textile composites to specific applications where flexibility or strength is prioritized.

Analysis of Mechanical Properties

Pineapple leaf fiber (PALF) exhibits intrinsic stiffness, high tensile strength, and biodegradability, rendering it a promising bio-filler for sustainable composites, particularly when combined with bioplastic matrices. Previous research on similar natural fibers, such as palm fibers, highlights their significant structural potential, with tensile strengths up to 1620 MPa and Young's moduli exceeding 24 GPa (e.g., mdpi.com citation). In this study, the integration of orange peel-derived bioplastic, rich in pectin and limonene, was hypothesized to enhance inter-fiber adhesion and composite flexibility. However, the overall mechanical properties, particularly tensile strength, remained predominantly governed by the PALF content and fabric weave pattern.

Tensile testing revealed an optimal balance of strength and elasticity within the 50–75% PALF content range. Plain and twill woven samples in this range achieved tensile strengths between 19 and 26 kgf. While these values were marginally below typical industrial PALF standards, they approached the Indonesian National Standard (SNI) thresholds for relevant textile applications. Conversely, higher PALF concentrations (75–100%) consistently resulted in a significant reduction in tensile strength. This phenomenon is attributed to the increased dominance of stiff, less conformable fibers at high loading, which disrupts effective stress transfer and load distribution within the bioplastic matrix. Despite this strength reduction, elongation values peaked at approximately 98% for these high fiber content samples, indicating a substantial increase in flexibility suitable for adaptive design applications.

These findings align with established principles in composite mechanics, where excessive fiber loading in certain matrices can lead to diminished flexibility and, beyond an optimum, even reduce overall strength due to fiber-fiber interference and reduced matrix impregnation. The observed trade-off between strength and elongation underscores the importance of optimizing fiber volume fraction. Therefore, the 50–75% PALF range represents a promising material formulation, offering an optimal synergy between tensile integrity and elasticity. This balance leverages the inherent natural, biodegradable, and tactile qualities of PALF, aligning with principles of biophilic and circular design.

The mechanical behavior of woven pineapple leaf fiber (PLF) composites is strongly influenced by fiber content, particularly affecting tensile strength and elongation characteristics. PLF inherently exhibits high stiffness, considerable fiber length, and coarseness, which contribute positively to tensile strength but tend to reduce flexibility at elevated concentrations. In this study, woven textiles were reinforced with a bioplastic coating derived from orange peel waste, which serves as both a natural binder and surface modifier. This bioplastic contains pectin and limonene, compounds known for their adhesive and elastic properties, enhancing fiber-fiber bonding and imparting surface flexibility to the composite.

At lower PLF contents (25–50%), the composite textiles demonstrated a balanced interplay between mechanical strength and flexibility. The PLF contributed to tensile strength, while the orange peel bioplastic maintained matrix homogeneity and elasticity across the weave structure. However, increasing PLF content to 75% and 100% resulted in a marked reduction in tensile strength, particularly in both plain and twill weave patterns. This decline is attributed to the predominance of stiff fibers, which impede uniform stress distribution, thereby creating localized stress concentrations that act as failure initiation points. Conversely, elongation at break increased significantly with higher PLF content, underscoring the bioplastic's role in enhancing composite elasticity.

Quantitatively, tensile strength measurements aligned with Indonesian National Standards (SNI) benchmarks, with a maximum recorded strength of 26.79 kgf for plain weave samples containing 25% PLF and a minimum of 11.75 kgf for twill weave samples at the same fiber content. Elongation values ranged from 65% to 98%, varying with weave architecture and fiber proportion. According to SNI and corroborating literature (Patel et al., 2020; Singh et al., 2021), minimum tensile strengths for suit fabrics are 23 kgf in the weft and 19 kgf in the warp directions.

While the composites did not reach the tensile strength levels reported for pure PALF fibers, this outcome is likely due to the incorporation of the softer, more flexible orange peel bioplastic, which enhances elongation but reduces overall structural rigidity. Additionally, the use of mixed fiber compositions and conventional weaving methods (plain and twill) may limit the full exploitation of PALF's intrinsic mechanical potential.

Nonetheless, the high elongation observed, up to 98% in plain weave samples with 100% PLF, indicates promising potential for applications requiring comfort, adaptability, and shape retention, particularly when combined with complementary structural supports. These findings resonate with sustainable design objectives emphasizing functionality, user experience, and environmental responsibility, consistent with biophilic design principles.

Moreover, the orange peel bioplastic contributes indirectly to improved surface softness, fiber homogenization, and interfacial adhesion, enhancing the tactile and visual qualities of the composite. Although it does not directly augment tensile strength, its role in improving comfort and aesthetics is critical for meeting sustainability certifications such as GOTS and ISO, especially when considering the full life cycle impact of textile materials.

3.8. Tensile Performance and Sustainability Relevance

Mechanical testing of the pineapple leaf fiber (PLF) and orange peel bioplastic composite shows an inverse relationship between tensile strength and fiber content: the highest strength (26.79 kgf) occurs at 25% PLF, while flexibility peaks at 98.31% elongation with 100% PLF. Although below industrial-grade PALF standards (>50 kgf), the material meets ISO and SNI thresholds for lightweight textiles. Comprising over 70% biodegradable natural fibers and produced without toxic chemicals, the composite supports sustainable, low-impact manufacturing (ISO 14001, ISO 20400) and utilizes agricultural waste through craft-based methods. Its flexibility, biodegradability, and community-centered production make it a promising alternative for eco-conscious textile applications.

3.9. Respondent Data and Material Perception Analysis

To complement the Material Driven Design (MDD) framework, qualitative data were collected via surveys and in-depth interviews with a purposively selected cohort of 30 respondents aged 20–30, primarily residing in urban regions such as Jabodetabek (Jakarta, Bogor, Depok, Tangerang, Bekasi) and Bandung. This demographic, comprising Generation Z and Millennials, is characterized by heightened awareness of sustainability and openness to novel material applications in lifestyle products. Participants included students, designers, creative professionals, and freelancers, enabling informed and critical evaluations of the visual, tactile, and functional potential of PLF and orange peel waste-derived materials.

This visual-focused exploration was conducted using eight material samples, developed based on the optimal bioplastic formulation and mechanical performance results identified in previous phases of the study. The samples included variations in weave structure (plain and twill), bioplastic volume (150 ml and 300 ml), composite forms combining textiles with bioplastic, and samples processed using a food dehydrator to examine surface and structural outcomes. Each sample was evaluated primarily for its visual characteristics, alongside texture, aroma, and the emotional impressions they evoked. The goal of this phase was to assess how different material treatments and compositions influence the aesthetic and sensory qualities of the biocomposite surfaces.

Twill weave samples received the highest visual preference, attributed to their dynamic texture and tactile softness, evoking associations with functional artisanal products such as canvas bags and placemats. Respondents noted a strong sense of familiarity and nostalgia linked to these materials.

The 300 ml bioplastic samples were distinguished by their deep caramel-orange coloration and leather-like texture, making them suitable candidates for outer-layer applications such as bags and wallets. The inherent orange scent was positively perceived as reinforcing the sustainable narrative, although respondents highlighted the need for improved scent consistency. Despite slight stickiness and rigidity, this variant was considered the most commercially promising.

Conversely, the 150 ml bioplastic samples, while visually appealing, lacked structural stability and exhibited inconsistent olfactory characteristics. Plain weave textiles were favored for foundational applications but were perceived as visually unremarkable. Dehydrator-processed samples were appreciated for their artistic uniqueness but deemed unsuitable for functional products due to uneven textures and overpowering aromas.

Based on these insights, the combination of twill weave fabric with the 300 ml bioplastic coating emerged as the most promising material pairing. This synergy integrates the mechanical robustness and tactile comfort of woven PLF with the aesthetic and sensory storytelling capacity of orange peel bioplastic. Collectively, they embody the principles of the Material Experience Framework (Karana et al., 2015), demonstrating how traditional craftsmanship and sustainable innovation can coalesce within MDD-driven design.

3.10. Discussion

This study employs Biophilic Design as a conceptual framework to guide the development of products that embody a harmonious relationship between people and nature. Biophilic principles are operationalized through the use of renewable natural materials, specifically, pineapple leaf fiber (PLF) and orange peel, and by exploring textures and visual expressions that highlight the organic character and inherent imperfections of these materials. The resulting materials are intended to fulfill not only functional requirements but also to provide a multi-sensory experience that evokes users' emotional affinity with nature

To translate biophilic values into material innovation, the Material Driven Design (MDD) approach was adopted. MDD centers the inherent properties and potential of materials, including visual, tactile, and structural qualities, as primary drivers for design and application. Systematic exploration of PLF and orange peel-based bioplastics enabled the identification of both aesthetic and technical attributes that inform product development. The integration of MDD and Biophilic Design in this study demonstrates the potential to create products that satisfy technical and sustainability criteria while simultaneously deepening the emotional connection between users and nature through materiality.

3.11. Sensory Perception and User Evaluation

A structured online questionnaire was administered to 30 respondents, primarily aged 20–30 years and with backgrounds in design and the arts. This demographic was purposively selected for its heightened awareness of sustainability and openness to material experimentation. While most respondents expressed familiarity with sustainable materials, regular use was limited, indicating a gap between awareness and practical adoption. Notably, while many had heard of PLF and bioplastics, direct interaction with such materials remained rare.

During the evaluation of the material samples, tactile and visual sensations were the most influential, with surface texture and appearance eliciting the strongest responses. The orange peel-based materials retained a mild fermentative aroma, which contributed to the multisensory experience.

The plain weave fabric was consistently described as neat, simple, and evocative of traditional woven crafts. The texture was perceived as rough and stiff, yet not uncomfortable, reinforcing the material's natural identity. Preferred color palettes included cream, off-white, natural yellow, and earthy tones, which were considered versatile for various design applications. Respondents valued the handmade quality, subtle orange scent, and orderly weave, often associating these characteristics with nostalgia and traditional craftsmanship.

Responses to the 150 ml and 300 ml orange bioplastic samples were diverse. The 150 ml variant was perceived as flexible but moist, with a translucent orange tone that suggested experimental potential. The 300 ml sample appeared more solid and caramel-colored, perceived as premium and suitable for product integration. Some respondents noted concerns regarding stickiness or slipperiness, questioning suitability for wearable applications, while others appreciated these as unique material expressions appropriate for narrative-driven or decorative products.

Samples produced using dehydrator techniques and whole orange peels exhibited expressive, cracked surfaces and gradient tones, though some respondents expressed reservations about strong odors and unstable textures. The scent, described variously as citrus fermentation, cinnamon, honey, or sour milk tea, was both a defining characteristic and a challenge for product stability. These findings are consistent with the assertion that material experience is inherently multisensory, involving sight, touch, scent, and sound.

Weaving and dyeing experiments with PLF and orange peel bioplastic received positive feedback, particularly for their visual and tactile qualities. The gradient effects and woven textures created dynamic experiences compared to uniform synthetic materials, and were viewed as "alive" and suitable for semifunctional or exclusive craft applications. The hand-dyed surface texture further enhanced the handcrafted feel, reinforcing the aesthetic value of imperfection and authenticity in design.

Respondents most frequently envisioned applications in fashion accessories (e.g., handbags, pouches, wallets), small bags, home décor, and interior organizers, favoring products with limited skin contact. These preferences reflect the material's visual and tactile characteristics, which were seen as more appropriate for medium-use aesthetic products than for flexible daily-wear textiles. Interior products such as table runners, lampshades, and storage baskets were also identified as promising applications, with respondents drawing associations to nostalgic and traditional home textiles.

Structurally, respondents imagined product forms such as boxes or shells with natural palettes (tan, light brown, muted oranges) and occasional expressive tones (bold blue, dusty pink). Emotionally, the materials evoked warmth, nostalgia, satisfaction, and curiosity. Some respondents recalled associations with vintage textiles and traditional crafts, while others described the materials as eccentric or delightful, underscoring the importance of multisensory engagement in material experience.

Scent remained a key factor: while some respondents were disturbed by the smell of fermentation or mustiness, others noted pleasant notes such as citrus or vanilla. Scent was thus identified as both a material identity and a challenge for product stability.

Symbolic meaning was explored through personification exercises, with responses ranging from mindful and spiritual to adaptive and artistic, highlighting the deep cultural and personal associations triggered by material properties. Respondents also shared specific memories triggered by texture and aroma, reinforcing the concept of material experience as rooted in social and personal memory.

4. Conclusion

This study presents the development of a biodegradable textile composite through the integration of handwoven pineapple leaf fiber (PLF) with bioplastic synthesized from orange peel waste. Utilizing the Material Driven Design (MDD) framework enabled a multidimensional assessment of the composite's mechanical, sensorial, and emotional properties, supporting a holistic approach to sustainable material innovation.

The fabrication process combined traditional weaving techniques—plain and twill patterns—with a bioplastic matrix composed of gelatin, glycerol, and water. A total of eight material variants were produced, with the twill-woven sample infused with 300 ml of orange peel bioplastic exhibiting the most favorable combination of tensile integrity, surface quality, and sensory appeal. Composites containing 50–75% PLF demonstrated an optimal balance between mechanical strength and flexibility, while the bioplastic matrix contributed to visual consistency and a characteristic citrus aroma, reinforcing the material's bio-based identity.

Mechanical testing revealed a trade-off between tensile strength and elongation: higher PLF content enhanced flexibility but reduced tensile resistance. Although tensile performance fell below industrial benchmarks for pure PALF composites, the developed materials satisfied relevant ISO and Indonesian National Standard (SNI) criteria for lightweight textile applications. Notably, the composites are fully biodegradable and produced through low-energy, chemical-free processes, aligning with circular economy principles and sustainability certification frameworks.

User perception studies with participants aged 20–30 (Generation Z and Millennials) revealed favorable evaluations of the material's texture, scent, and aesthetic, confirming its suitability for design applications such as fashion accessories, interior textiles, and lifestyle products. These findings underscore the effectiveness of MDD in capturing intangible material qualities, such as emotional engagement and user affinity, that extend beyond conventional performance metrics.

The incorporation of Biophilic Design principles further strengthens the composite's value proposition by enhancing human–material connections through natural textures, olfactory cues, and visual irregularities. This positions the material not only as a sustainable textile alternative but also as a vehicle for experiential, multisensory engagement.

From a commercial perspective, the material demonstrates promising potential for eco-conscious fashion and interior products due to its unique tactile quality, biodegradability, and aesthetic appeal. However, scaling up production poses challenges in maintaining consistency, durability, and environmental stability, as the bioplastic matrix is sensitive to humidity and prone to mold growth. These issues underscore the need for further formulation improvement, preservation methods, and controlled production environments. The research process itself revealed these material instabilities as major obstacles, reflecting the broader difficulty of balancing natural composition with modern durability standards. Despite these challenges, the project highlights an important step toward integrating local craft traditions with sustainable material innovation for future market adoption.

In conclusion, this research affirms the Material Driven Design methodology as a valuable framework for developing circular, biophilic materials that harmonize technical functionality with cultural and emotional relevance. The integration of PLF and orange peel-derived bioplastics offers a scalable pathway for advancing sustainable innovation within the textile and materials science sectors.

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