Cleaner Engineering and Technology 31 (2026) 101190

Contents lists available at ScienceDirect

Cleaner Engineering and Technology

journal homepage: www.sciencedirect.com/journal/cleaner-engineering-and-technology

Exploring haptic perception of Natural Fiber Reinforced Polymer Composites for product design

Annabella Narganes-Pineda [a,*], Pedro M. Hernández-Castellano [a], Lucía Rodríguez-Parada [b], Miguel-Angel Pardo-Vicente [b]

[a] *Mechanical Engineering Department, University of Las Palmas de Gran Canaria, Escuela de Ingenierías Industriales y Civiles, Campus de Tafira, Las Palmas de Gran Canaria, Las Palmas, 35017, Spain*

[b] *Department of Mechanical Engineering and Industrial Design, University of Cadiz, Escuela Superior de Ingeniería, Avenida de La Universidad de Cádiz, Puerto Real, Cádiz, 11519, Spain*

ARTICLE INFO

Keywords:
Product design
Material selection
Natural fiber reinforced polymer composites
Haptic perception
Circular design

ABSTRACT

The increasing demand for sustainable materials has accelerated the development of Natural Fiber Reinforced Polymer Composites (NFRPCs). However, while their mechanical and environmental performance has been studied, little attention has been paid to how users perceive these materials through touch and how such perceptions influence their acceptance in product design. This study addresses this gap by exploring the integration of haptic perception into the evaluation of NFRPCs within the framework of circular design. A haptic experiment was conducted with 116 participants, who evaluated rotomolded NFRPC samples differing in polymer matrix, fiber type, and sieved-fiber size. Drawing on the frameworks of Material Driven Design and Soft Metrology, the research combines objective surface characterization with subjective sensory assessment to identify how tactile experience shapes perceived material quality, functionality, and aesthetic value. Results indicate that user perception is more strongly influenced by matrix and fiber characteristics than by surface roughness alone. PLA-based composites were generally perceived as higher in quality and more aesthetically appealing, whereas PE-based composites were associated with functional use and lower perceived quality. The study demonstrates the relevance of integrating experiential and technical evaluation methods in early design stages. This approach contributes to developing perceptually engaging and sustainable materials, fostering user-centered innovation in circular product design.

1. Introduction

Conventional fiber-reinforced composites, particularly those based on glass and carbon fibers, have long been valued for their high strength-to-weight ratio and durability. However, their production relies heavily on energy-intensive processes and non-renewable resources, while their limited recyclability contributes to long-term environmental burdens (Das et al., 2023). As global industries transition toward more sustainable material systems, increasing attention is being directed toward alternatives that combine mechanical performance with reduced ecological impact (Joustra et al., 2021). In this context, Natural Fiber Reinforced Polymer Composites (NFRPCs) have emerged as a promising alternative due to their unique combination of lightweight properties, mechanical strength, and biodegradability (Ajayi et al., 2025). NFRPCs consist of natural fibers embedded within a polymer matrix, providing structural performance comparable to conventional synthetic composites while maintaining a substantially lower environmental footprint (Elfaleh et al., 2023). Their potential to reduce environmental impact while delivering high-performance solutions has positioned NFRPCs at the forefront of sustainable design strategies, particularly in industries such as automotive, construction, and consumer product (Ghalme et al., 2025).

Responding to this challenge, Circular Design emerges like an enabler to Circular Economy (Adilah et al., 2023; Wastling et al., 2018). This philosophy and workflow seek to address social, economic, and environmental challenges by promoting the reuse of materials, product longevity, and waste minimization throughout lifecycle (Narganes-Pineda et al., 2025). Previous research has identified resource conservation as one of its core principles, emphasizing the efficient use and reuse of materials. This principle is particularly

---

* Corresponding author.
E-mail address: annabella.narganes@ulpgc.es (A. Narganes-Pineda).

https://doi.org/10.1016/j.clet.2026.101190
Received 19 August 2025; Received in revised form 28 February 2026; Accepted 8 March 2026

relevant in NFRPCs, as it supports the transformation of agricultural or invasive plant residues into valuable raw materials, thereby extending their utility and contributing to more sustainable production systems.

Although the mechanical properties of NFRPCs have been widely studied, research on the integration of technical and sensory properties in material selection remains limited (Abella et al., 2022; Piselli et al., 2018). This study explores users' haptic perception of NFRPCs, focusing on how sensory attributes influence the evaluation of material quality and functionality. Its primary goal is to incorporate perceptual and emotional responses into material design and selection, thereby enhancing both user experience and product performance (Iosifyan and Korolkova, 2019; Wan et al., 2021).

To this end, a haptic perception experiment is proposed, focusing on the relationship between functionality and aesthetics as well as the perception of low- and high-quality surfaces. Integrating haptic perception with soft metrology provides a comprehensive framework for the exploration of the evaluation of NFRPCs from a user-centered perspective, extending the analysis beyond mechanical performance. While previous studies have predominantly focused on the technical optimization of natural fiber composites, this research introduces an experiential dimension that links tactile perception with material functionality and quality evaluation. By combining quantitative surface data with users' sensory responses, the study offers a novel methodological approach to understanding how material attributes shape perception and acceptance. This integration provides valuable insights for product designers seeking to balance functionality, aesthetics, and sustainability, ultimately contributing to the development of sustainable materials that are not only technically efficient but also perceptually meaningful and socially accepted.

2. Conceptual Framework

To support this inquiry, the following section outlines conceptual foundations that inform the study. It presents an overview of NFRPCs and examines their relevance in the context of circular product design. Furthermore, it also introduces complementary frameworks, Material Driven Design (MDD), soft metrology and multisensory evaluations, that help connect technical properties with user perception. Together, these perspectives support a more integrated understanding of how material characteristics influence tactile experience and product acceptance.

NFRPCs, also known as Natural Fiber Composites (NFC), have attracted considerable attention in recent years due to their potential as sustainable alternatives to synthetic composites (Ajayi et al., 2025). These composites incorporate plant-based fibers as reinforcement within polymer matrices. Compared to traditional synthetic composites, they offer several advantages, including favorable mechanical properties, low density, reduced production costs, the use of renewable resources and biodegradability. The growing demand for sustainable materials has accelerated the development and widespread adoption of NFRPCs, as they present a promising alternative to glass or carbon fiber composites by reducing reliance on fossil fuels and mitigating environmental impact. Nevertheless, these materials also face certain limitations, such as high moisture absorption, low dimensional stability, and limited interfacial compatibility between fiber and matrix. NFRPCs are still under development and with relatively limited industrial applications (Elfaleh et al., 2023; Ghalme et al., 2025).

To further enhance the sustainability of composite materials, it is essential to prioritize the use of renewable raw materials, improve recyclability and reduce environmental impact by increasing efficient resource use (Marconi et al., 2022; Suárez et al., 2021a). Within this framework, NFRPCs are especially valuable, as they are derived from renewable plant-based sources and can often be recycled or biodegraded at the end of their life cycle, thereby closing the material loop and minimizing waste (Ghalme et al., 2025). Studies have shown that natural fibers, such as flax and hemp, require significantly less energy to produce than conventional glass fibers, resulting in a lower carbon footprint (Munimathan et al., 2024). Additionally, replacing synthetic reinforcements with natural alternatives improves the overall environmental profile of composites, especially in industries such as automotive, packaging, and construction (Mohammed et al., 2024; Santhosh et al., 2024). However, NFRPCs still face challenges in achieving the same mechanical performance and durability as synthetic counterparts. As industries face stricter regulations and rising demand for sustainable products, the ability of NFRPCs to unite technical performance with environmental responsibility positions them as strategic materials for eco-conscious design (Ajayi et al., 2025).

In this context, the valorization of invasive plant species as a source of natural fibers for composite production offers a unique opportunity to address both environmental degradation and material sustainability (Ortega et al., 2021). Invasive species such as *Ricinus communis, Arundo donax L.*, *Pennisetum setaceum*, and *Agave americana L.* pose a serious threat to ecosystems in the Macaronesia archipelagos, Madeira, Azores, and the Canary Islands, by disrupting local biodiversity, altering soil composition, and increasing fire risk due to excessive biomass (Suárez et al., 2021b). Given their widespread presence and the ecological damage they cause, these species have been classified as invasive by both national and regional environmental authorities (Ortega et al., 2021). Their integration into composite materials not only contributes to ecosystem restoration efforts by promoting biomass removal but also supports Circular Design principles by converting waste into high-value, functional materials.

Within the scope of product design and development, materials selection is a multidisciplinary process that influences both the technical configuration and the aesthetic expression of a product. Traditionally, engineers and designers have approached this process from different epistemologies: engineers rely on propositional and quantitative data, such as mechanical resistance and manufacturing constraints, while designers focus on sensorial and expressive aspects using qualitative descriptors and material mood boards (Piselli et al., 2018). This divergence often leads to misalignment in the selection of materials, particularly in the early stages of product development. Recent research highlights the need to integrate these perspectives by establishing frameworks that link measurable material properties to sensorial and emotional user responses, thus enabling informed decisions that are both technically robust and experientially meaningful (Bergman et al., 2020; Eriksson et al., 2018; Thundathil, 2025).

In line with the growing emphasis on sustainability and the need for more meaningful material experiences, research in design has shifted toward understanding not only what materials are, but also what they do, how they feel, and how they shape user experience (Rognoli et al., 2015). The MDD Method, introduced by Karana et al. (2015), offers a structured approach to designing with and for materials when the material itself is the point of departure. Rather than focusing solely on performance or technical criteria, MDD integrates functional, emotional, and experiential aspects into the design process. It emphasizes the active role of materials in shaping user-product interactions, encouraging designers to explore what a material expresses, what it elicits from the user, and how it invites action. MDD Method defines four sequential action steps: (1) Understanding the Material: Technical and Experiential Characterization, (2) Creating Materials Experience Vision, (3) Manifesting Materials Experience Patterns, (4) Designing Material/Product Concepts (Karana et al., 2015).

This approach is particularly relevant in the context of NFRPCs, which, beyond their environmental benefits, possess distinct tactile and aesthetic qualities that can influence perception and acceptance (Abella et al., 2022). By applying MDD, designers can balance sustainability with sensorial richness, aligning material innovation with both functional requirements and affective engagement. In this context, NFRPCs are not merely sustainable substitutes but also expressive materials that communicate environmental values and emotional meaning within product experiences (Taekema and Karana, 2012).

Within the MDD Method's first step, Understanding the Material, it is critical to capture not only objective material metrics but also users' experiential responses. Here, soft metrology provides a guideline for the measurement of perceived quality by capturing users' sensory and emotional responses to a product's material and surface properties, complementing the objective data of hard metrology (e.g., surface roughness measurements) (Bergman et al., 2020). To trace the relationship between manufacturing processes, material properties and perceived quality, it is essential to integrate user-centered studies into the evaluation protocol (Eriksson et al., 2018).

A user-centered experimental protocol requires the systematic involvement of users throughout the evaluation process, ensuring that material-related decisions are grounded in substantial experiential evidence rather than designer intuition alone (Gherardini et al., 2017). Such protocols define when and how users participate, positioning them as active contributors in the elicitation of requirements, the evaluation of alternatives and the assessment of final outcomes. This structured involvement supports the translation of user perceptions and preferences into design-relevant criteria through objective and repeatable methods, reducing subjectivity in decision-making (Gherardini et al., 2017).

Complementary, design toolkits and experimental frameworks embed principles of user acceptance and adoption across different stages of design and evaluation, helping designers reflect on behavioral, cognitive, and affective factors that influence material acceptance (Bobrova and Perego, 2026). Experimental protocols are particularly valuable for capturing how physical material qualities elicit interconnected meanings and emotions, which are not perceived as isolated attributes but as relational and coexisting experiences shaped through sensory interaction (Kapkın and Joines, 2025). Moreover, empirical studies demonstrate that even subtle variations in fabrication and material processing can significantly affect tactile and aesthetic perception, reinforcing the need for experimental setups that explicitly connect manufacturing parameters with perceptual evaluation (Urquhart and Wodehouse, 2023).

In practice, this approach entails designing experiments that elicit intuitive, affective and cognitive reactions, the impressions that ultimately drive acceptance and satisfaction. Design research emphasizes that material perception arises from multisensory experiences that integrate visual, tactile, and cognitive processes (Dong and Liu, 2017). Understanding how these sensory dimensions interact, allow designers to assess materials not only by their technical performance, but also by their experiential impact (Silvennoinen and Mononen, 2023). Within this framework, Kansei Engineering (KE) provides a systematic method for translating users' emotional and sensory responses into design parameters, linking objective data with subjective perception (Yanagisawa and Miyazaki, 2019; Yang and Jia, 2009). Among these modalities, haptic perception, the sense of touch and evaluation of texture, softness and roughness, plays a crucial role in shaping judgments of quality and functionality, influencing both their emotional response and purchasing behavior (Nordvik et al., 2009; Spence and Gallace, 2011; Yanagisawa and Miyazaki, 2019). By integrating haptic perception, this study seeks to uncover how the tactile properties of NFRPCs affect user perception and how these insights can inform sustainable product design.

3. Materials and method

A structured approach was adopted to research the haptic perception of rotomolded samples of NFRPCs in product design. This study integrates insights from surface characterization and material selection process to examine how different NFRPCs characteristics impact on user perception and product acceptance. By combining soft metrology (subjective sensory evaluation) and hard metrology (objective measurement of surface properties), this approach provides a comprehensive understanding of material perception. The methodology addresses both the functional and aesthetic dimensions of material evaluation, reflecting the dual role of performance and perception in sustainable product design.

To achieve this, the study is organized into four key components. Firstly, the research questions are defined in order to guide the investigation, identifying the gaps in the Conceptual Framework to shed light on the connection between hard and soft metrology. Secondly, the material sample provides a description of the samples used in the experiment. Thirdly, the experiment description outlines the design and execution of a haptic perception test, detailing the sample preparation, participant selection, and evaluation criteria. Finally, the data processing section presents the analytical methods used to quantify the responses, providing a structured framework.

Through this approach, both the technical and perceptual properties of NFRPCs are analyzed in a comprehensive manner. By linking haptic perception with material performance, this study aims to generate relevant insights for improving product design and user acceptance of sustainable materials.

3.1. *Research question*

The increasing demand for sustainable materials has led to a growing interest in NFRPCs not only due to their environmental advantages but also for their potential to meet both technical and aesthetic expectations in product design (Palanisamy et al., 2024). However, while much research has focused on their mechanical and environmental performance, a significant gap remains in understanding how these materials are perceived by users (Abella et al., 2022), especially through the sense of touch (Iosifyan and Korolkova, 2019). This sensory dimension plays a critical role in user acceptance and satisfaction, particularly in the context of product interaction and sustainability communication (Thundathil, 2025).

By integrating a material selection methodological framework, this study explores the haptic perception of various rotomolded NFRPCs samples and how these relate to user evaluations of functionality, aesthetic appeal, and perceived material quality. This work also considers the technical characterization of surface properties (hard metrology) alongside user-centered perception data (soft metrology) to provide a comprehensive understanding of how tactile information influences product perception.

The following research questions have been formulated to guide this research. These questions are presented in a logical sequence, progressing from the exploration of users' tactile experiences with NFRPCs samples to the development of tools and design strategies that integrate both user perception and technical characterization.

- How do users perceive the tactile qualities (roughness, softness, texture) of NFRPCS samples, and how do these perceptions influence the evaluation of this material in a product?
- What types of evaluation tools or test protocols can effectively capture haptic perception and user preferences for NFRPCS in an industrial design context?
- How can the integration of soft and hard metrology contribute to the development of more user-accepted, sustainable product designs using NFRPCS?

By addressing these questions, this study seeks to contribute to a better understanding of the relationship between material performance, sensory perception, and sustainable product development. Rather than providing definitive answers, the research aims to explore how subjective and objective evaluation criteria might be integrated in the selection of NFRPCs for Circular Design, while also opening up new questions for future investigation. To support this exploration, a structured haptic perception experiment was developed to examine how users interact with NFRPCs samples through touch, and how these interactions influence their evaluations of functionality, aesthetics, and perceived quality.

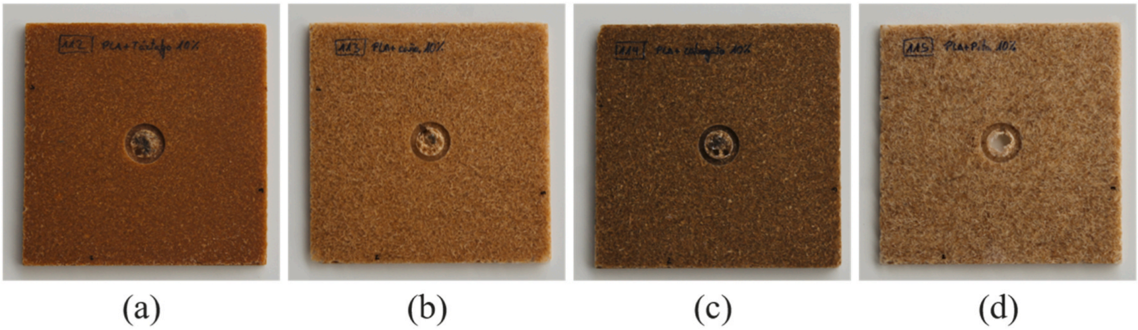


Fig. 1. PLA-based composites reinforced with 10% untreated fiber. (a) *Ricinus communis,* TA; (b) *Arundo donax L.,* CA; (c) *Pennisetum setaceum,* RG; (d) *Agave americana L.,* PI.

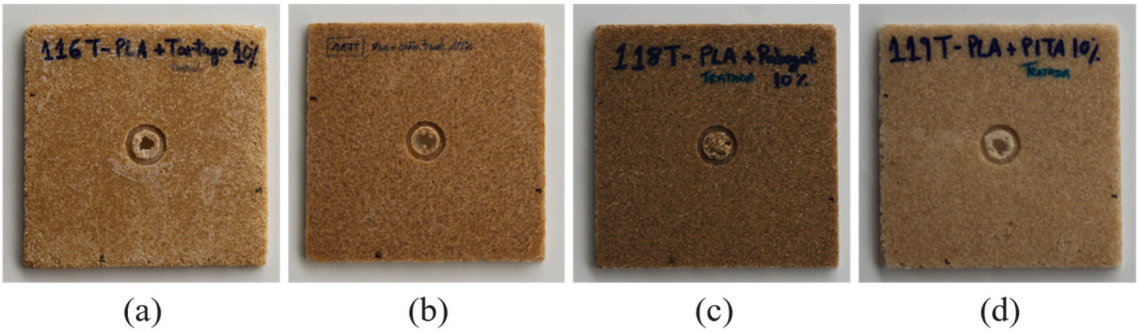


Fig. 2. PLA-based composites reinforced with 10% treated fiber. (a) *Ricinus communis,* TA; (b) *Arundo donax L.,* CA; (c) *Pennisetum setaceum,* RG; (d) *Agave americana L.,* PI.

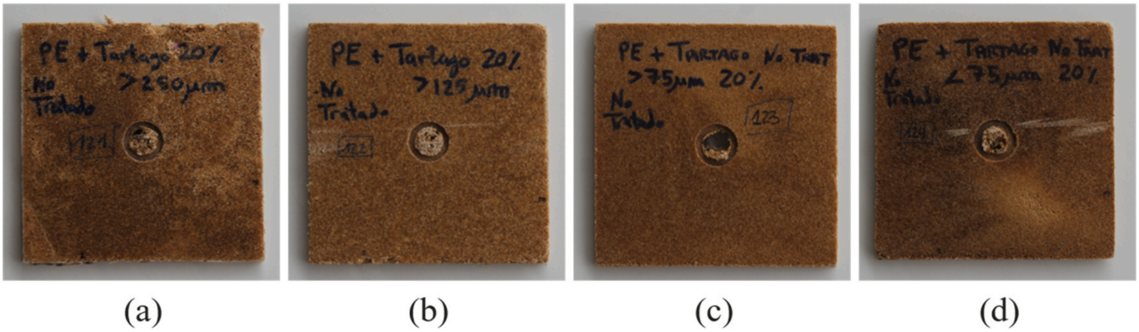


Fig. 3. PE-based composites reinforced with 20% untreated TA fiber. Sieved Fiber Size (a) > 250 μm; (b) > 125 μm; (c) > 75 μm; (d) < 75 μm.

3.2. Material samples

This section describes the material samples used in the haptic experiment. The experimental set consisted of rotomolded NFRPCs samples varying in polymer matrix (PLA and PE), fiber type, fiber treatment, and sieved fiber size. A total of 16 samples were used, systematically labeled from A to P, and categorized according to their formulation parameters. Each sample measured 120 × 120 mm with an approximate thickness of 5 mm, ensuring consistent dimensions for comparative evaluation. These combinations were selected to enable the comparative assessment of surface tactile properties. The samples were obtained from previous research conducted by the Integrated and Advanced Manufacturing Research Group at the University of Las Palmas de Gran Canaria, funded by the European Funding for Regional Development.

Samples A–D consist of PLA-based composites reinforced with untreated natural fibers at a 10% weight ratio. These samples were selected to examine the influence of different fiber types on haptic perception under consistent polymer and treatment conditions. Fig. 1 illustrates samples A to D, highlighting the visual similarities and differences despite their shared matrix and untreated fiber condition.

Building on this, samples E–H also use a PLA matrix with 10% fiber content, but the fibers have undergone chemical treatment. This group was included to assess whether fiber treatment affects tactile feedback, potentially altering perceptions of quality or aesthetics. Fig. 2 presents samples E to H, allowing comparison between treated and untreated PLA composites.

Samples I–L shift the matrix to PE and incorporate untreated *Ricinus communis L.* (TA) fibers at a 20% weight ratio, with fiber size controlled through sieving across four granulometric ranges. This group enables an exploration of how fiber size variation within the same treatment and matrix affects surface texture and user evaluation. Fig. 3 shows samples I to L, grouped according to decreasing fiber size.

Finally, samples M–P maintain the same PE matrix and fiber content as I–L but use chemically treated TA fibers, with the same sieved fiber size distinctions. These allow for analysis of the combined effects of

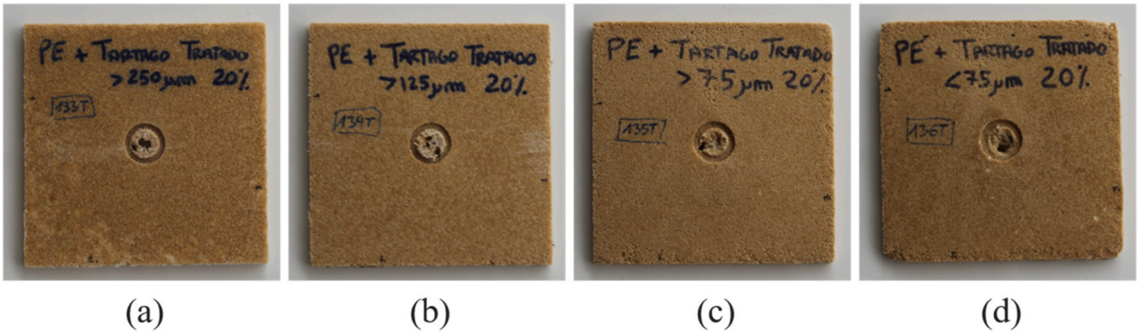


Fig. 4. PE-based composites reinforced with 20% treated TA fiber. Sieved Fiber Size (a) > 250 μm; (b) > 125 μm; (c) > 75 μm; (d) < 75 μm.

Table 1
Material samples description.

Sample	Matrix	Natural Fiber	NF Acronym	%	Treatment	Sieved Fiber Size
A	PLA	*Ricinus communis*	TA	10	No	Non-sieved
B	PLA	*Arundo donax L.*	CA	10	No	Non-sieved
C	PLA	*Pennisetum setaceum*	RG	10	No	Non-sieved
D	PLA	*Agave americana L.*	PI	10	No	Non-sieved
E	PLA	*Ricinus communis*	TA	10	NaOH	Non-sieved
F	PLA	*Arundo donax L.*	CA	10	NaOH	Non-sieved
G	PLA	*Pennisetum setaceum*	RG	10	NaOH	Non-sieved
H	PLA	*Agave americana L.*	PI	10	NaOH	Non-sieved
I	PE	*Ricinus communis L.*	TA	20	No	>250 μm
J	PE	*Ricinus communis L.*	TA	20	No	>125 μm
K	PE	*Ricinus communis L.*	TA	20	No	>75 μm
L	PE	*Ricinus communis L.*	TA	20	No	<75 μm
M	PE	*Ricinus communis L.*	TA	20	NaOH	>250 μm
N	PE	*Ricinus communis L.*	TA	20	NaOH	>125 μm
O	PE	*Ricinus communis L.*	TA	20	NaOH	>75 μm
P	PE	*Ricinus communis L.*	TA	20	NaOH	<75 μm

treatment and size on perceived material properties. Fig. 4 depicts samples M to P, facilitating a direct comparison with their untreated counterparts.

A detailed overview of the composition and processing characteristics of each sample is provided in Table 1. This table summarizes the key variables for all 16 material specimens, including polymer matrix, fiber type, fiber content, treatment condition, and sieved fiber size.

3.3. Experiment description

To explore how users perceive the tactile qualities of NFRPCs and evaluate them in terms of functionality, aesthetics, and quality, a controlled haptic evaluation experiment was designed. The aim was to simulate a real-world interaction with materials through touch, while eliminating visual biases. This setup allowed the collection of quantitative and qualitative user feedback based on haptic perception and served to test the effectiveness of a tactile evaluation matrix as a design-oriented assessment tool.

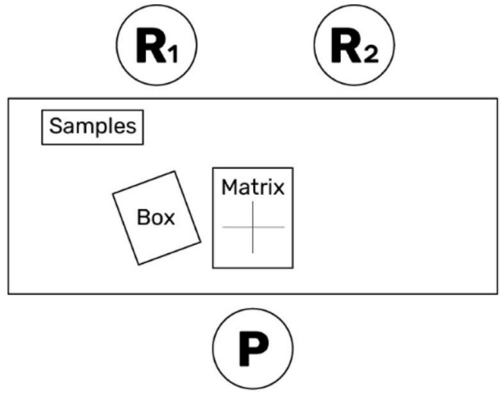


Fig. 5. Experiment setup. P is participant, R1 and R2 researchers.

The experiment was conducted in a classroom equipped with a table and three chairs, one for the participant (P) and two for the researchers (R1, R2). Upon entering the room, each participant was seated following the configuration shown in Fig. 5.

At the beginning of the experiment the participants are required to fill out a questionnaire. This questionnaire gathered demographic information (number of participants, gender, age and professional/academic background) and user profile information (designed to assess the participant's orientation towards traditional versus environmentally conscious attitude).

The second part of the experiment involved a haptic evaluation task. An A3-sized printed matrix was placed on the table, featuring two axes as shown in Fig. 6.

- The X-axis ranged from 0% aesthetic and 100% functional on the left to 100% aesthetic and 0% functional on the right, with a midpoint indicating an equal balance between both.
- The Y-axis ranged from (bottom to top) low to high perceived quality.

At the bottom of the matrix, reference images of various plastic products were provided, arranged progressively from purely functional to highly aesthetic designs. The sequence began with a traffic barrier, followed by a watering can, an outdoor bench, a seesaw toy, a luminaire, and finally, a decorative figure. All these products are manufactured using the same process as the samples evaluated in the study: rotational molding. To ensure visual consistency and prevent color or material finishes from influencing participants' interpretations, all images were presented in black and white. This decision was made to homogenize visual stimuli and allow participants to focus on the form and perceived function of the products, aligning with the study's emphasis on haptic perception and material qualities.

In front of the participant a closed box with a single hand-sized

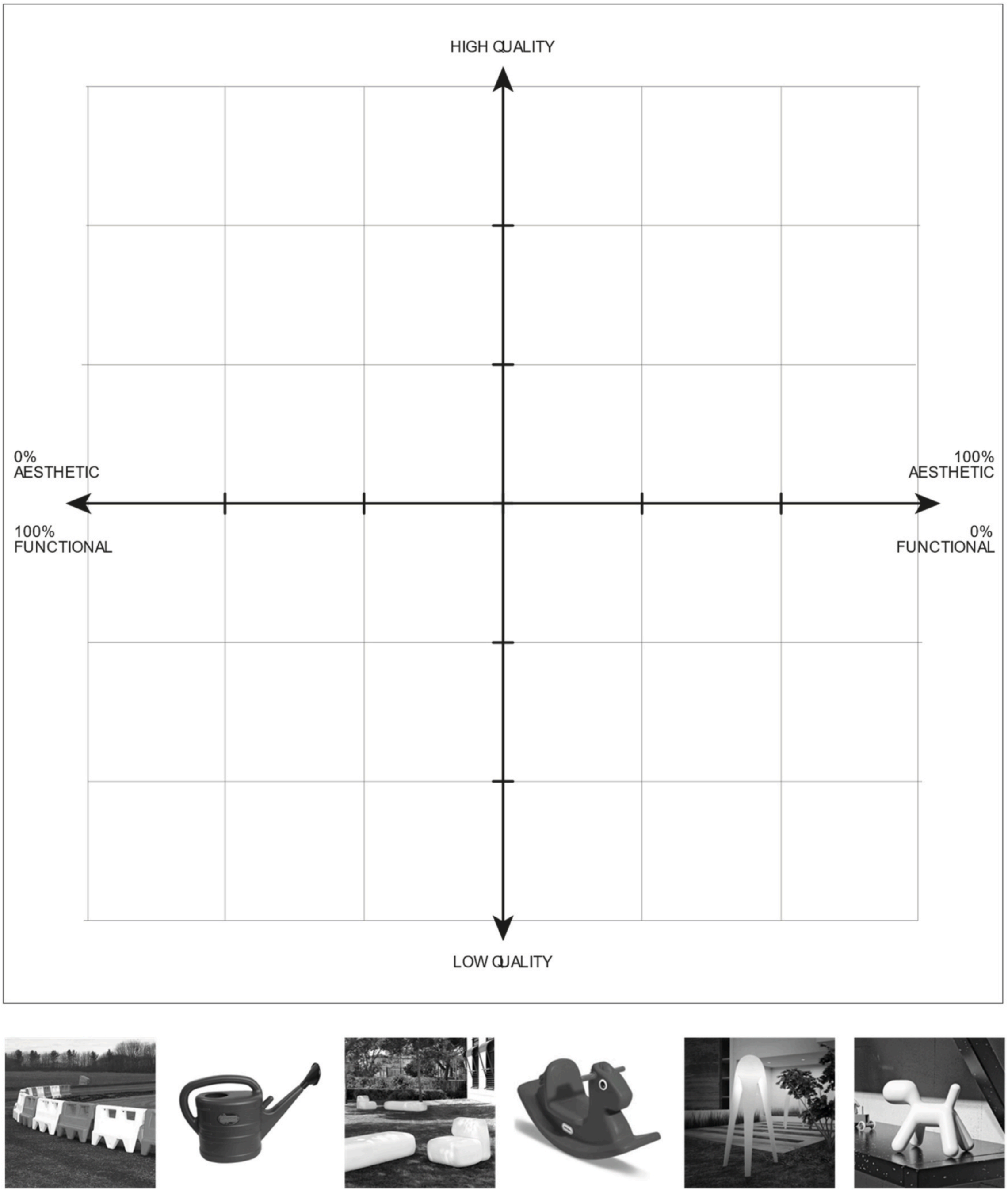


Fig. 6. Experiment matrix.

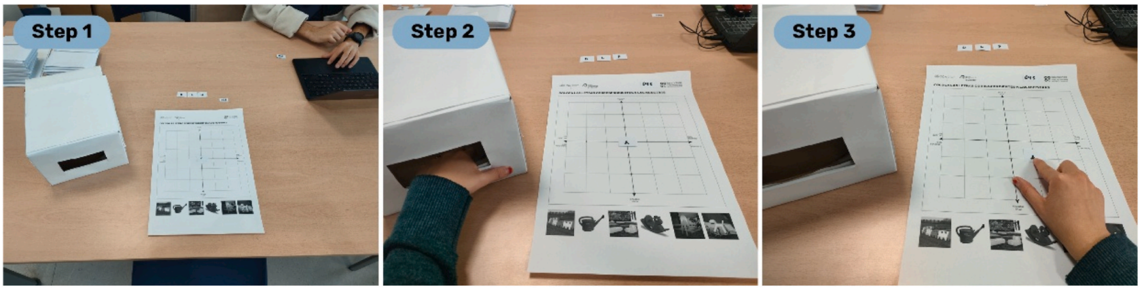


Fig. 7. Experiment steps. From left to right: first step explanation of the experiment; second step touch the sample; third step place the sample's letter on the matrix.

opening is placed. Inside, the material samples are introduced one at a time, each placed in an envelope with a small window to expose a limited tactile area. This setup ensures that participants can only assess the samples through touch, visual inspection and manipulation are not allowed. Each sample is assigned a letter, and participants are instructed to place this letter on the matrix according to their tactile impressions regarding functionality, aesthetic appeal, and perceived material quality. These steps are presented in Fig. 7.

Each session lasts approximately 10 min, with at least 3 min between participants to reset the setup. Every participant evaluates four samples, randomly selected from a total of 16 samples described in the previous section. This experimental design enables the collection of user-centered data related to tactile perception, while also supporting a cross-analysis of subjective impressions and objective surface measurements within a sustainable material design context.

3.4. Measuring procedure

Following the experimental sessions, data analysis was conducted to interpret both the quantitative surface measurements and the qualitative perceptual responses gathered from participants. This was done with the aim of uncovering patterns and correlations between the measured surface roughness of each NFRPCs sample and the users' tactile-based evaluations, particularly in relation to perceived functionality, aesthetics, and quality.

Prior to the user evaluations, all samples underwent surface roughness analysis to obtain objective measurements of their tactile properties. Surface roughness was measured using an *Alicona InfiniteFocus G5* variable focus microscope. The use of this microscope was made possible through the support of the Research Group Materials and Manufacturing Engineering and Technology at the University of Cádiz. For each sample, three measurements were taken from three different areas of the surface to ensure reliable and representative data. These values serve as a technical counterpart to the participants' perceptual responses and are intended to be correlated through a soft and hard metrology framework.

As mentioned above, this study comprises both qualitative and quantitative data. Quantitative measurements, obtained from confocal surface measurements, were evaluated through Arithmetic Average Roughness (Sa) parameter. This parameter was evaluated by calculating the mean of the three trials of each NFRPCs sample to ensure consistency and accuracy. Qualitative measurements were represented graphically to facilitate visualization and comparative analysis. For both quantitative and qualitative measurements, the software *RStudio* was employed for data processing.

4. Results and discussion

This section presents the results and discussion of the haptic and surface roughness assessment of the mentioned samples, focusing on the influence of polymer type, as well as fiber treatment, type and size on the perceived quality and functionality. A comparative study was made, analyzing the distribution of the results across the proposed matrix, which enabled the identification of tendencies and perception variation. Surface roughness measurements were also observed in order to identify any potential correlations with perception.

4.1. Participants profile

A total of 116 individuals participated voluntarily in the experiment. The sample was composed of 65 men, 50 women, and 1 non-binary participant, with ages ranging from 18 to 65 years. Age distribution was as follows: 55% were between 18 and 24, 22% between 25 and 34, and 23% between 35 and 65. In terms of academic and professional background, 72% of participants reported belonging to the Engineering and Architecture disciplines. The experiments were conducted at the Superior School of Engineering of the University of Cádiz, the School of Industrial and Civil Engineering and the General Library of the University of Las Palmas de Gran Canaria. Efforts were made to include participants across all age ranges to ensure representativeness in perceptual diversity. The sample size was appropriate for exploratory haptic perception studies, offering a balance between statistical reliability and practical feasibility while capturing a wide range of user evaluations.

Table 2
Participant profile questionnaire statements.

S1	I am concerned about the environmental impact of the products I use daily
S2	I am willing to change my consumption habits in order to be more sustainable
S3	I do not mind paying more for products thar are eco-friendly of sustainable
S4	I closely follow the latest trends and technological advancements
S5	I prefer to remain loyal to traditional materials in my everyday products
S6	I feel comfortable using products made from unconventional materials

In addition to the demographic data, participants completed a brief Likert-type questionnaire designed to assess individual orientation toward more traditional versus environmentally conscious preferences. The scale included four levels (from “Strongly Disagree” to “Strongly Agree”) across a set of statements reflecting sustainability values and consumption attitudes (see Table 2). The results of this self-assessment participant profile questionnaire are presented in Fig. 8.

Overall, the responses indicate a participant group that is highly oriented toward sustainability and open to innovation. A substantial majority expressed concern about the environmental impact of their daily consumption (88.8% agreement), and an even greater proportion (86.3%) reported a willingness to alter their habits to support more sustainable practices. While a majority (62%) also indicated that they are willing to pay more for environmentally friendly products, this statement received relatively more disagreement compared to the others, suggesting that economic considerations may still present a barrier for a notable subset of participants.

Participants also demonstrated a marked interest in technological innovation, with 74.1% indicating that they follow new trends and advancements. Conversely, traditionalism in material preference appears to be relatively low, as only 36.2% endorsed loyalty to conventional materials, and 81.1% reported feeling comfortable using products made from unconventional materials. Taken together, these findings suggest that the sample is characterized by a progressive consumer profile, environmentally conscious, adaptable in consumption behavior, and receptive to both innovation and non-traditional product solutions.

4.2. Results

The following section presents the results obtained from the haptic perception experiment, focusing on how participants evaluated the tactile qualities of the NFRPC samples and how these evaluations relate to perceived functionality, aesthetics, and material quality. As a result of a general comparison between all PLA and PE samples, both treated and untreated, differences in perceived quality and functionality were observed. In general, PLA samples were perceived as higher quality, while a tendency toward functionality was observed in PE samples (see Fig. 9).

When comparing untreated and treated samples, untreated PLA samples showed a marked tendency toward high-quality perception, with no clear distinction between aesthetic and functional perception, although a slight inclination toward aesthetic perception was observed. In contrast, treated PLA samples exhibited more dispersed results, maintaining the lack of functional and aesthetic distinction with a mild tendency toward higher quality. PE samples, regardless of treatment, showed a greater dispersion, with a tendency toward functionality. Untreated PE presented a more compact distribution, with moderate quality perception. Treated PE samples, on the other hand, displayed a broader dispersion and a slight tendency toward lower quality. It was considered important to note that the differences between treated and

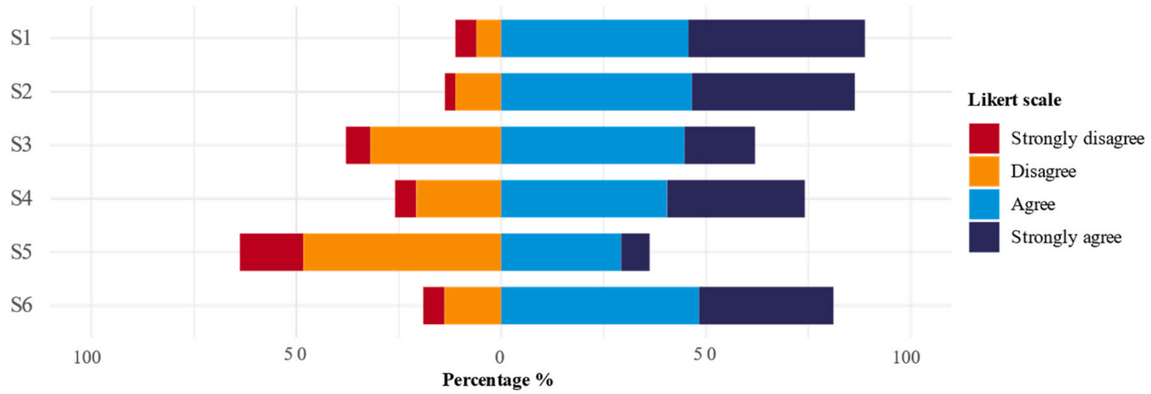


Fig. 8. Results of participants profile questionnaire. The X-axe represents the percentage of participants in each level of the Likert scale. The Y-axes represents the statements.

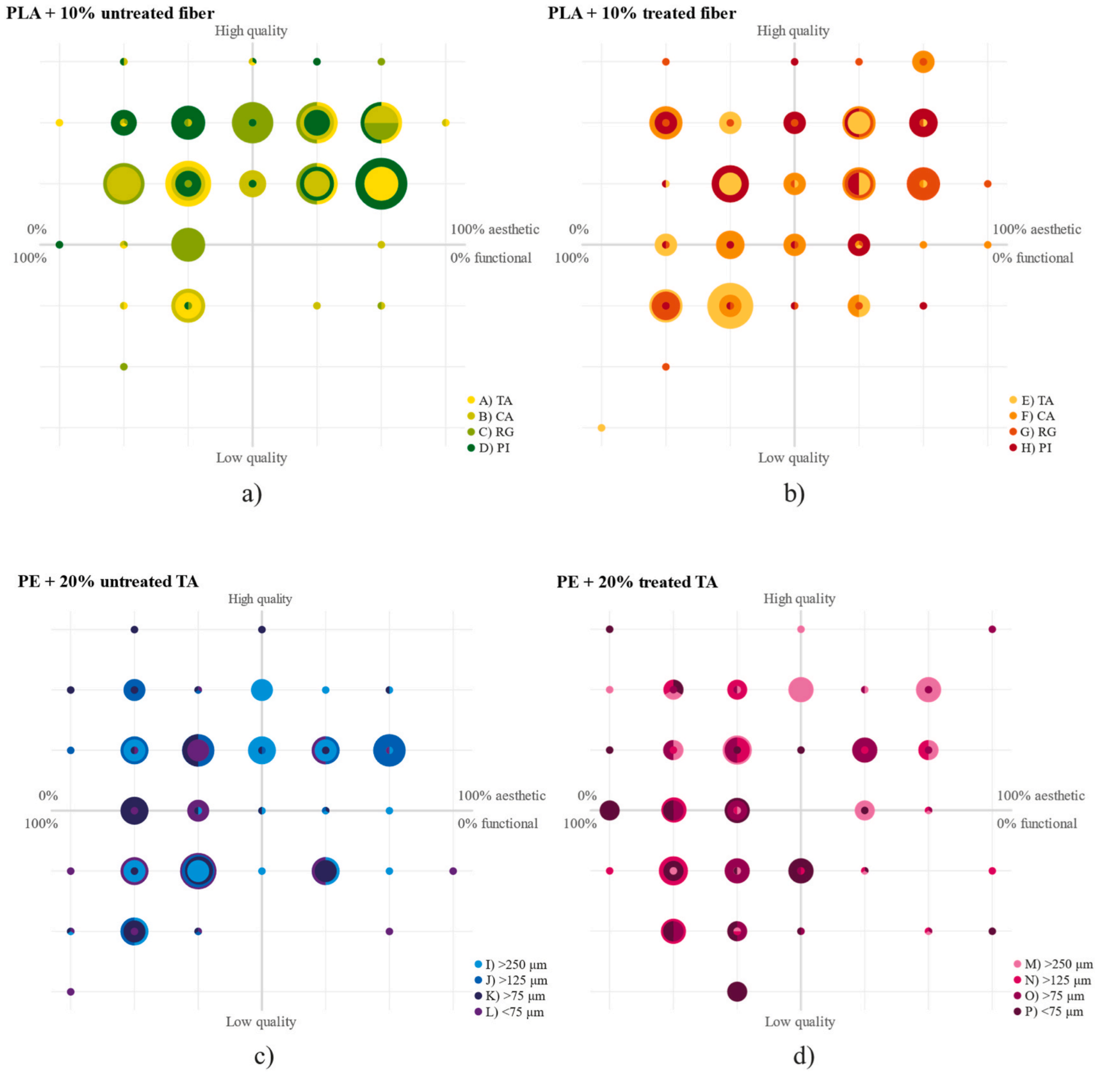
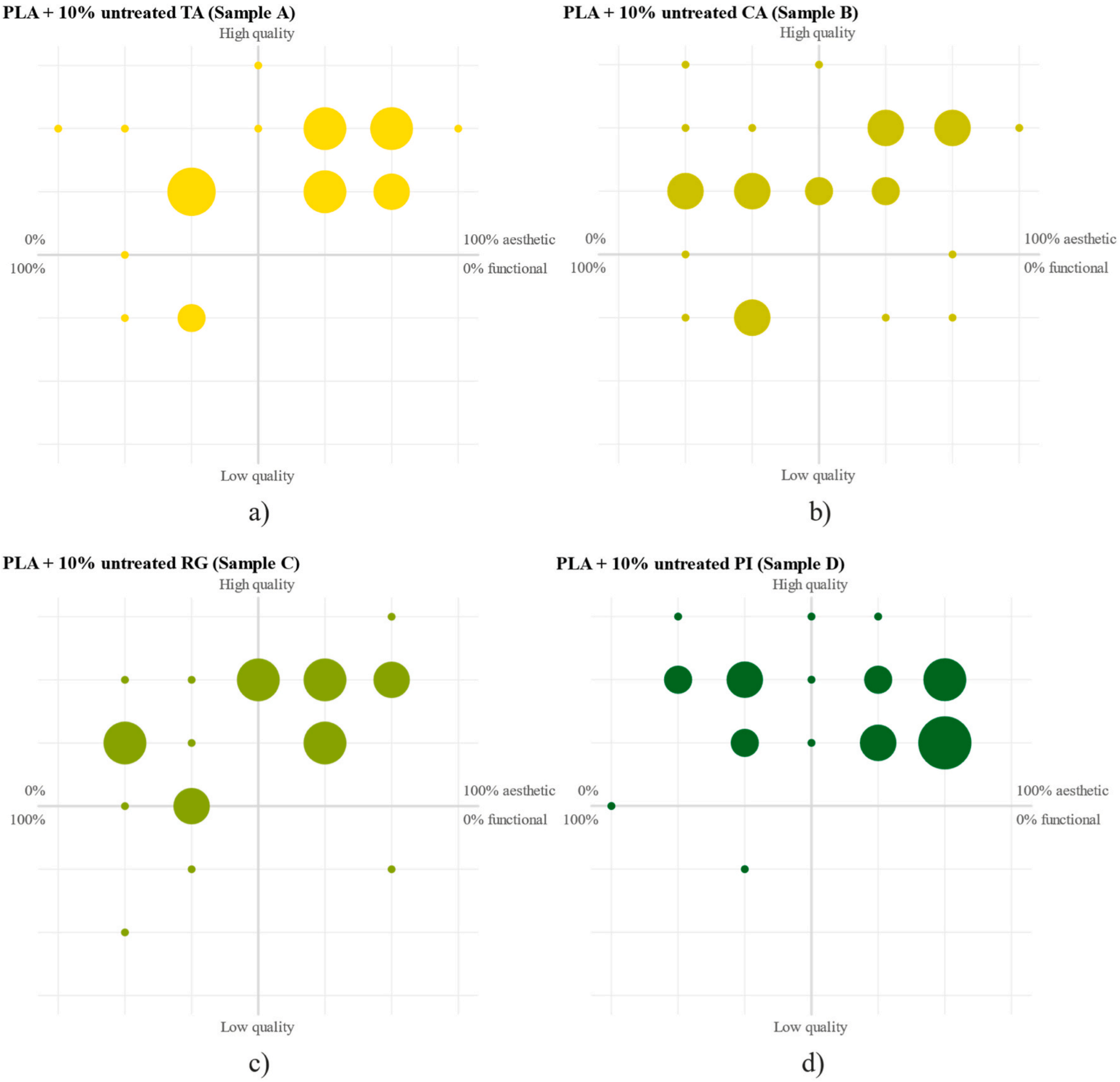


Fig. 9. PLA (a) (b) and PE (c) (d) samples results. The graphs represent the results of the experiment. The colors, as indicated in each legend, represent each type of natural fiber in (a) and (b), and the fiber sieving size in (c) and (d). The X-axis ranged aesthetic vs functional. The Y-axis ranged perceived quality. The size of each circle corresponds to the number of responses at that point, the larger the circle, the greater the number of responses.

untreated PLA samples were considerably greater than those observed for PE, as observed in the figure above.

Withing PLA untreated natural fibers samples, little variation was observed among fiber types. TA and PI showed a tendency toward highly aesthetic and high-quality perception, while RG showed a similar tendency but with a less marked preference. CA was perceived as medium quality, with no clear distinction between functionality and aesthetic purposes, with a weaker tendency toward high-quality than the rest. To



a)

b)

c)

d)

Fig. 10. PLA and 10% untreated natural fibers samples results. The size of each circle corresponds to the number of responses at that point, the larger the circle, the greater the number of responses.

better observe this variation, Fig. 10 provides a breakdown of the responses presented in Fig. 9(a)

In contrast, treated PLA samples showed greater dispersion overall. TA shifted toward lower quality and functionality, while CA remained toward high-quality and aesthetic purposes with a tendency toward neutrality. RG exhibited high dispersion with a slight tendency toward high-quality and aesthetic purposes, while PI remained perceived as high-quality without functionality/aesthetic distinction but with more dispersed results than its untreated counterpart (see Fig. 11).

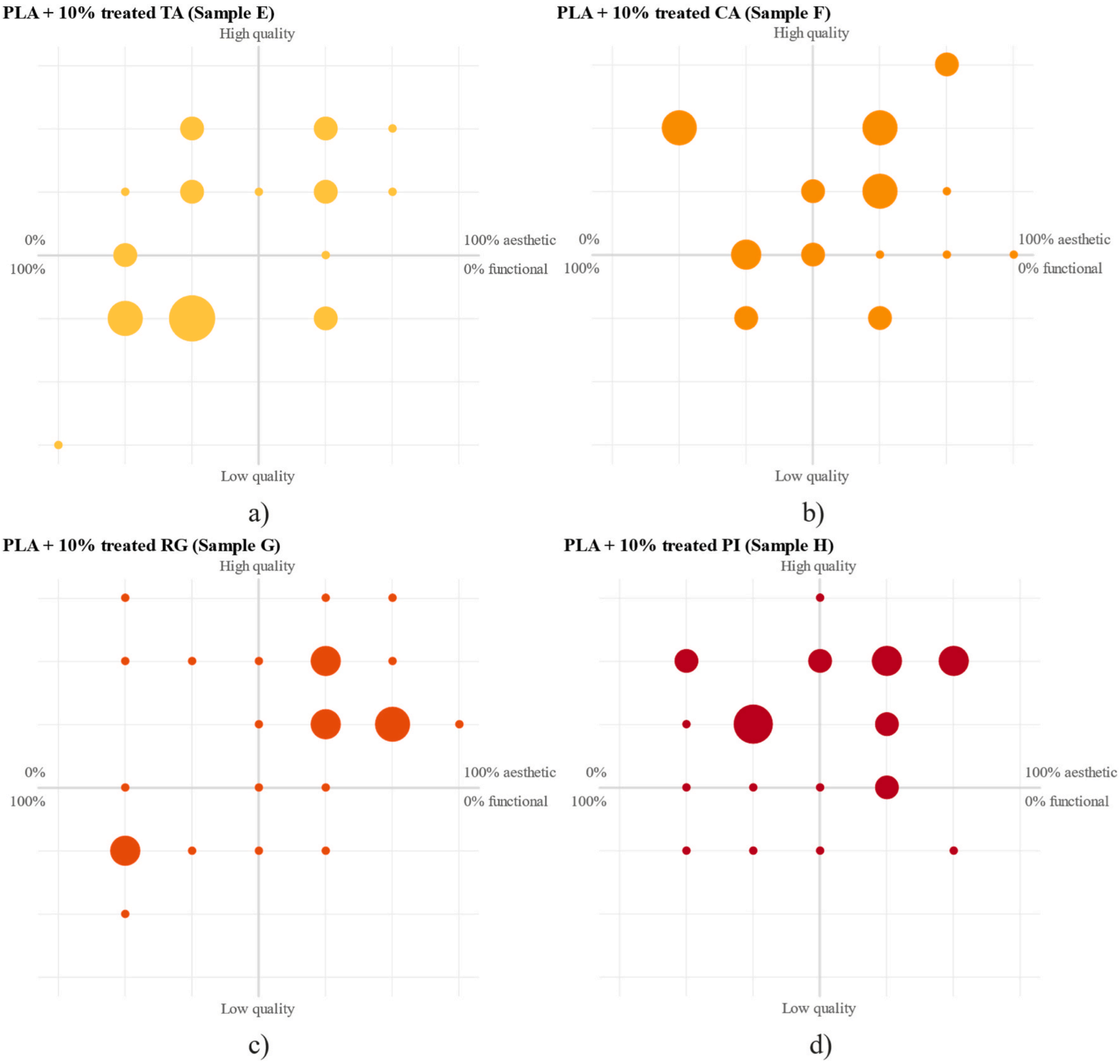
In untreated PE samples, dispersion patterns varied with fiber size (see Fig. 12). Fiber size superior to 250 μm and inferior to 75 μm presented similar dispersion levels but differed in perception-the first had no clear tendency while the second showed a tendency toward functionality and lower quality. Fiber size superior to 75 μm presented the most dispersion, with a dominant functional association. Fiber size superior to 125 μm was perceived as both higher and lower quality, with a strong tendency toward functionality.

In treated PE samples, dispersion increased across all fiber sizes (see Fig. 13). Fiber sizes superior to 125 μm and 75 μm, as well as those inferior to 75 μm, tended toward a functional perception, with no distinction of quality and a preference toward lower quality for fiber size inferior to 75 μm. Fiber size superior to 250 μm, however, a higher quality perception was observed when compared to the others.

When evaluating surface roughness results, it was observed that PLA samples, regardless of treatment, presented a lower roughness when compared to PE samples (see Fig. 14). Sample E was observed to have a noticeable higher value than the rest of PLA samples, as well as increased variability in values. This is due to the measurement of a rough area within the sample, where the polymeric matrix did not fully coat the natural fibers, resulting in a distortion of the surface roughness measurements. When comparing haptic and surface roughness results, the variability of the results obtained prevents the identification of any direct relation or tendency. Several samples present very similar surface roughness values, such as C and D, G and H or L and M, but are perceived very differently by users.

4.3. *Discussion*

The results reveal notable differences in users' haptic perception of NFRPC depending on the type of polymer and fiber characteristics. Untreated PLA samples consistently exhibited a higher perceived quality, with a slight tendency toward aesthetic use, regardless of fiber type. This contrasts with PE composites, which are generally associated with functional applications and medium or undefined perceived quality,



a) b) c) d)

Fig. 11. PLA and 10% treated natural fibers samples results. The size of each circle corresponds to the number of responses at that point, the larger the circle, the greater the number of responses.

particularly in the untreated condition.

In addition to being based on different polymer matrices, these samples also differ in fiber content. The PLA-based samples contain 10% fiber, whereas the PE-based samples incorporate 20% fiber. This distinction suggests a possible trend: surfaces with higher fiber content tend to be perceived as more functional. While further analysis would be required to isolate this variable, the data indicates that fiber loading may influence not only mechanical properties but also user perception of material functionality.

The impact of fiber treatment was more pronounced in PLA-based composites than in PE. While treated PLA samples showed greater dispersion in perceptual evaluations, they maintained a general trend toward high perceived quality. However, this trend was less marked than in untreated PLA samples, suggesting that fiber treatment may introduce haptic features that reduce consistency in perceived performance. In PE composites, surface treatment did not substantially alter the functional perception but slightly shifted evaluations toward lower quality, possibly due to changes in surface texture or fiber–matrix interaction.

Regarding fiber type, haptic distinctions were more evident in untreated PLA-based composites. For instance, untreated TA and PI fibers were strongly associated with an aesthetic appearance and high perceived quality. Untreated CA and RG showed similar tendencies, although the association was less pronounced. In treated PLA samples, TA exhibited a noticeable shift toward a perception centered on functionality and lower quality, suggesting a deterioration in tactile coherence due to the treatment. RG and PI retained their association with aesthetic and high-quality attributes, although with greater variability in perception.

When considering fiber size, the differences were shown in PE samples. Fiber size influenced both the consistency of responses and the perceptual positioning of the samples. Smaller fibers (e.g., <75 μm), particularly in treated conditions, were predominantly associated with functional applications and low perceived quality. In contrast, some larger fiber sizes (e.g., >250) remained closer to the aesthetic–high quality domain, indicating a more favorable perception. These results suggest that fiber size modulates surface characteristics in a non-linear way, affecting the balance between perceived functionality and quality.

The notion that increased fiber visibility or heterogeneity introduces tactile cues that shift perception toward utility-oriented meanings. Such findings resonate with Karana's (2012) argument that the inherent irregularities of bio-based materials can communicate “naturalness,” which users may interpret as a distinct aesthetic value rather than a defect (Karana, 2012). Rather than striving to mimic the perfectly uniform surfaces of synthetic plastics, embracing these “imperfect” sensory properties may enhance the meaningful differentiation of NFRPCs in

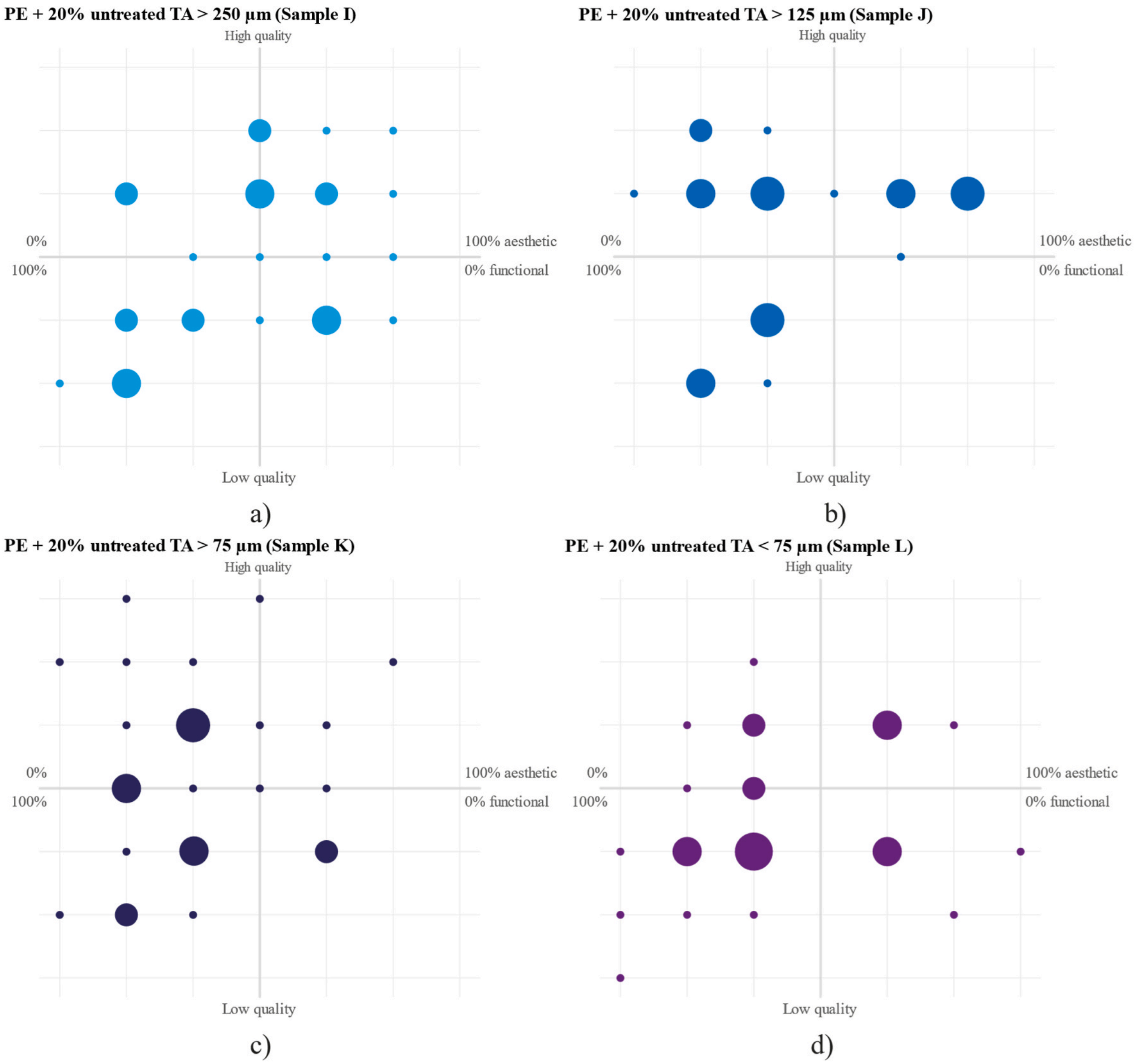


Fig. 12. PE and 20% untreated TA samples results. The size of each circle corresponds to the number of responses at that point, the larger the circle, the greater the number of responses.

product applications.

Surface roughness does not seem to have a direct impact on the haptic perception of the samples. Although PLA-based composites generally exhibit lower surface roughness values compared to PE-based ones, perceptual responses within each matrix type show considerable variability. This variability is not consistently reflected in the measured roughness parameters, suggesting that other factors may play a more prominent role in shaping tactile evaluation, such as matrix characteristics, fiber orientation or fiber distribution. This supports prior findings that measurable surface parameters alone cannot fully predict subjective sensory experiences (Piselli et al., 2018). As Piselli and colleagues argue, physical measurements are valuable for characterizing surface attributes but are insufficient to describe the aesthetic or experiential dimension of materials, hence the need to complement hard metrology with qualitative sensory analysis.

This study reinforces the value of integrating soft metrology into early material evaluation, supporting the idea that sensory analysis enables the inclusion of users' preferences and expectations in early product development stages (du Bois et al., 2021; Veelaert et al., 2020). Moreover, the perceptual sensitivity identified in participants resonates with broader consumer trends: anticipated moral or environmental conscience has been shown to increase acceptance and purchase intention toward sustainable materials (Magnier et al., 2019). In this sense, understanding how NFRPCs feel is not merely a technical concern but a determinant of their market adoption.

Overall, these findings demonstrate that haptic perception of NFRPCs emerges from a complex interplay between polymer matrix, fiber characteristics and experiential meanings. For product design, this suggests that the sensorial perception of NFRPCs could be strategically leveraged to align material properties with desired functional or aesthetic intentions. Moreover, the results point to the potential of these composites in applications where tactile interaction is central to user experience, such as consumer goods, automotive interior components and outdoor furniture, thus supporting the future development of sustainable materials that are not only technically viable but also perceptually coherent and more likely to be accepted by users.

5. Conclusion

This study explored the haptic perception of NFRPCs in a product design context, to understand how users interpret surface properties such as texture, softness, and roughness, and how these perceptions influence the evaluation of sustainable materials. The results provide insight into how perceptual evaluation methods can support material selection in circular product design, complementing traditional approaches.

Using a structured framework grounded in Material Driven Design, Soft Metrology and multisensory evaluations, the research explored how

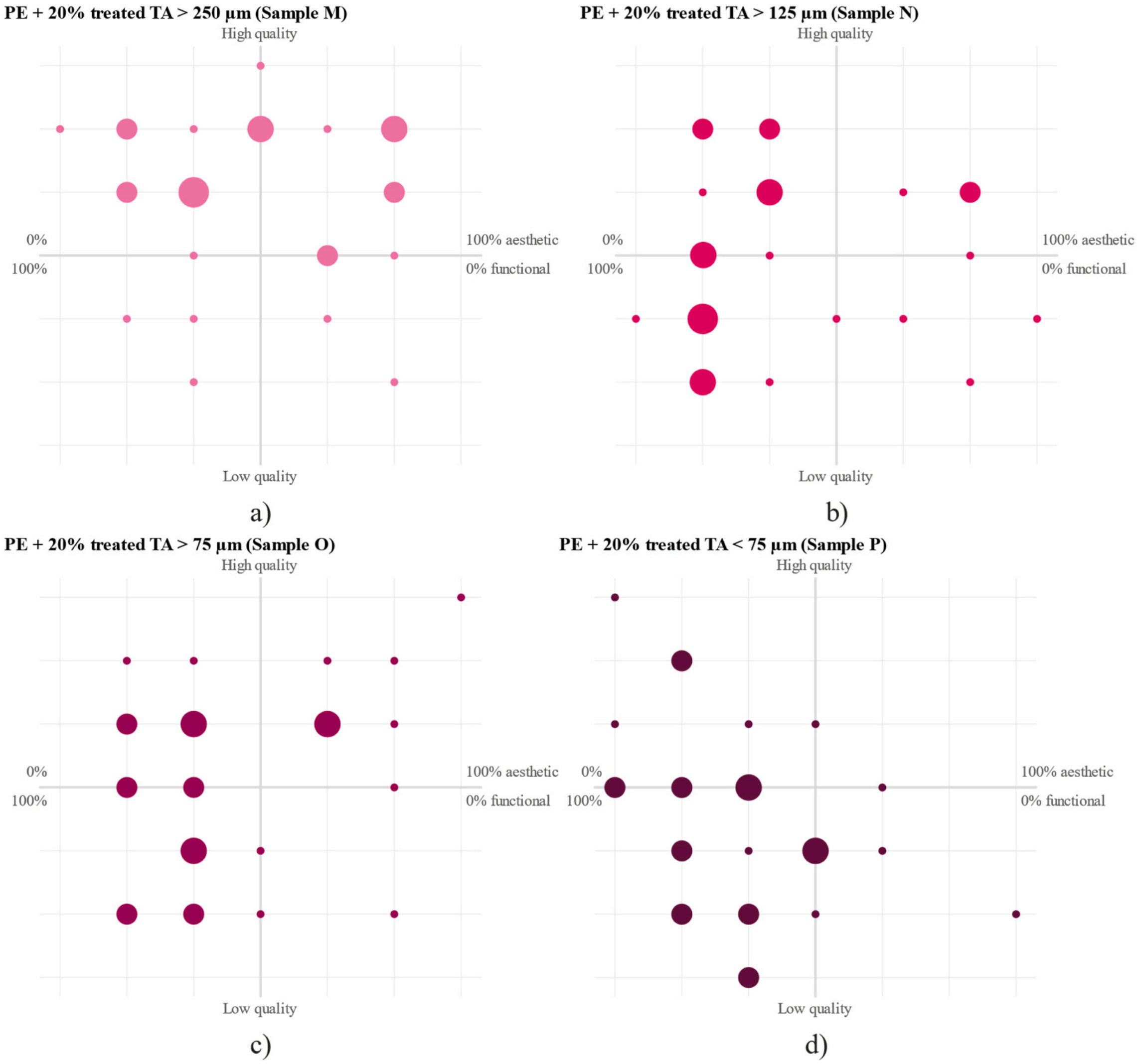


Fig. 13. PE and 20% treated TA samples results. The size of each circle corresponds to the number of responses at that point, the larger the circle, the greater the number of responses.

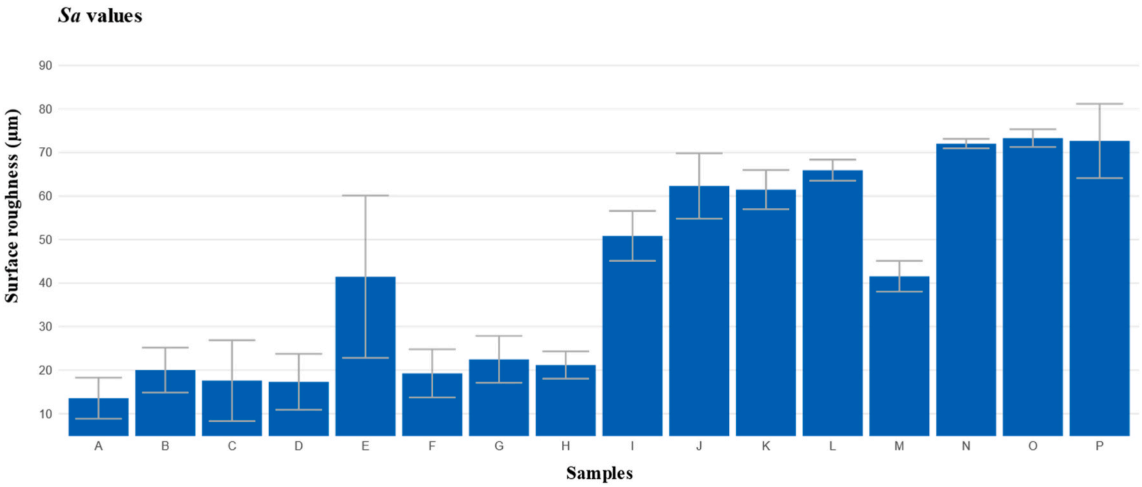


Fig. 14. Surface roughness *Sa* values. *Sa* is the arithmetical mean height. The X-axis represents each sample: A to H correspond to the PLA matrix, and I to P to the PE matrix.

polymer matrix, fiber type, treatment, and size affect user perception. PLA-based composites, particularly those with untreated fibers, are consistently perceived as aesthetically appealing and of higher quality. In contrast, PE-based samples, especially those with smaller and treated fibers, are more strongly associated with functional use and lower perceived quality. Higher fiber content (20% in PE) tends to increase functional perception, suggesting that users are sensitive to material composition rather than purely surface features. Fiber treatment, meanwhile, appears to introduce greater perceptual variability, occasionally disrupting tactile coherence without necessarily enhancing quality perception.

No clear correlation is found between measured surface roughness (Sa) and users' tactile evaluations, indicating that haptic perception results from a more complex combination of physical and sensory parameters, such as matrix type, fiber orientation and distribution. These findings highlight the relevance of combining hard metrology (quantitative surface data) with soft metrology (qualitative perceptual responses) to capture the multisensory and affective dimensions of material experience.

A hybrid test protocol was developed, integrating haptic exploration with a quality–purpose matrix, allowing participants to intuitively classify materials along perceived axes of quality and functionality. This approach demonstrates the potential of user-centered testing tools to complement material characterization and design decision-making for emerging composites.

The study's exploratory nature imposed certain limitations. The range of materials was restricted to samples from previous research rather than those fabricated specifically to isolate experimental variables. Nonetheless, this approach was suitable for testing and refining the proposed evaluation framework. Participant diversity, while adequate for exploratory purposes, did not fully represent the broader population.

Future research should focus on producing tailored sample sets to isolate specific parameters, broadening participant demographics and enhancing test protocols. Further exploration of multisensory interactions, particularly between visual and haptic perception, could provide a more comprehensive understanding of how users evaluate sustainable materials. Expanding these methods will strengthen the integration of subjective experience into material development, promoting NFRPCs that are not only technically efficient but also perceptually engaging and socially accepted within circular design frameworks.

CRediT authorship contribution statement

Annabella Narganes-Pineda: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft. **Pedro M. Hernández-Castellano:** Investigation, Project administration, Resources, Supervision, Validation, Writing – review & editing. **Lucía Rodríguez-Parada:** Conceptualization, Resources, Supervision, Validation, Writing – review & editing. **Miguel-Angel Pardo-Vicente:** Conceptualization, Methodology, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The samples were obtained from previous research that was funded by European Funding for Regional Development (FEDER), INTERREG MAC 2014–2020 program, providing funds for MAC ecoFIBRAS project (Grant number MAC/4.6d/040) and Inv2Mac (Grant number MAC2/4.6d/229).

The authors would like to thank the Research Group Materials and Manufacturing Engineering and Technology at the University of Cádiz for providing access to the Alicona InfiniteFocus G5 variable focus microscope.

Work co-financed by the Agencia Canaria de Investigación, Innovación y Sociedad de la Información de la Consejería de Economía, Conocimiento y Empleo y por el Fondo Social Europeo (FSE) Programa Operativo Integrado de Canarias 2014–2020, Eje 3 Tema Prioritario 74 (85 %).

Data availability

Data will be made available on request.

References

Abella, A., Llorach-Massana, P., Pereda-Baños, A., Marco-Almagro, L., Barreda-Ángeles, M., Clèries, L., 2022. Perception of recycled plastics for improved consumer acceptance through self-reported and physiological measures. Sensors 22 (23). https://doi.org/10.3390/s22239226.

Adilah, M., Rau, H., Procopio, K.M., 2023. Using an axiomatic design approach to develop a product innovation process with circular and smart design aspects. Sustainability 15 (3). https://doi.org/10.3390/su15031933.

Ajayi, N.E., Rusnakova, S., Ajayi, A.E., Ogunleye, R.O., Agu, S.O., Amenaghawon, A.N., 2025. A comprehensive review of natural fiber reinforced Polymer composites as emerging materials for sustainable applications. In: Applied Materials Today, 43. Elsevier Ltd. https://doi.org/10.1016/j.apmt.2025.102666.

Bergman, M., Rosen, B.G., Eriksson, L., Lundeholm, L., 2020. Material & Surface design methodology - the user study framework. Surf. Topogr. Metrol. Prop. 8 (4). https://doi.org/10.1088/2051-672X/ab915f.

Bobrova, P., Perego, P., 2026. A design toolkit for user acceptance and adoption: supporting designers in complex technology development. Univers. Access Inf. Soc. 25 (1). https://doi.org/10.1007/s10209-025-01286-4.

Das, S.C., La Rosa, A.D., Goutianos, S., Grammatikos, S., 2023. Effect of accelerated weathering on the performance of natural fibre reinforced recyclable polymer composites and comparison with conventional composites. Composites Part C: Open Access 12. https://doi.org/10.1016/j.jcomc.2023.100378.

Dong, Y., Liu, W., 2017. A research of multisensory user experience indicators in product usage scenarios under cognitive perspective. Int. J. Interact. Des. Manuf. 11 (4), 751–759. https://doi.org/10.1007/s12008-016-0358-8.

du Bois, E., Veelaert, L., Tormans, E., Moons, I., 2021. How should plastic recyclates look like to be perceived as sustainable: a first exploration. Proceedings of the Design Society 1, 1765–1774. https://doi.org/10.1017/pds.2021.438.

Elfaleh, I., Abbassi, F., Habibi, M., Ahmad, F., Guedri, M., Nasri, M., Garnier, C., 2023. A comprehensive review of natural fibers and their composites: an eco-friendly alternative to conventional materials. In: Results in Engineering, 19. Elsevier B.V. https://doi.org/10.1016/j.rineng.2023.101271.

Eriksson, L., Rosen, B., Bergman, M., 2018. Affective Surface engineering-using Soft and Hard Metrologhy to Measure the Sensation and Perception in Surface Properties.

Ghalme, S., Hayat, M., Harne, M., 2025. A comprehensive review of natural fibers: bio-based constituents for advancing sustainable materials technology. In: Journal of Renewable Materials, 13. Tech Science Press, pp. 273–295. https://doi.org/10.32604/jrm.2024.056275. Number 2.

Gherardini, F., Renzi, C., Leali, F., 2017. A systematic user-centred framework for engineering product design in small- and medium-sized enterprises (SMEs). Int. J. Adv. Manuf. Technol. 91 (5–8), 1723–1746. https://doi.org/10.1007/s00170-016-9857-9.

Iosifyan, M., Korolkova, O., 2019. Emotions associated with different textures during touch. Conscious. Cognit. 71, 79–85. https://doi.org/10.1016/j.concog.2019.03.012.

Joustra, J., Flipsen, B., Balkenende, R., 2021. Circular design of composite products: a framework based on insights from literature and industry. Sustainability 13 (13). https://doi.org/10.3390/su13137223.

Kapkın, E., Joines, S., 2025. Exploring the relationships between product meanings. Int. J. Ind. Ergon. 106. https://doi.org/10.1016/j.ergon.2025.103697.

Karana, E., 2012. Characterization of “natural” and “high-quality” materials to improve perception of bio-plastics. J. Clean. Prod. 37, 316–325. https://doi.org/10.1016/j.jclepro.2012.07.034.

Karana, E., Barati, B., Rognoli, V., van der Laan, A.Z., 2015. Material driven design (MDD): a method to design for material experiences. Int. J. Des. 9. www.ijdesign.org.

Magnier, L., Mugge, R., Schoormans, J., 2019. Turning ocean garbage into products – consumers' evaluations of products made of recycled ocean plastic. J. Clean. Prod. 215, 84–98. https://doi.org/10.1016/j.jclepro.2018.12.246.

Marconi, M., Bakshi, B., Joustra, J., Bakker, C., Bessai, R., Balkenende, R., 2022. Circular composites by design: testing a design method in industry. https://doi.org/10.3390/su14137993.

Mohammed, M., Oleiwi, J.K., Mohammed, A.M., Jawad, A.J.M., Osman, A.F., Adam, T., Betar, B.O., Gopinath, S.C.B., 2024. A review on the advancement of renewable natural fiber hybrid composites: prospects, challenges, and industrial applications. In: Journal of Renewable Materials, 12. Tech Science Press, pp. 1237–1290. https://doi.org/10.32604/jrm.2024.051201. Number 7.

Munimathan, A., Muthu, K., Subramani, S., Rajendran, S., 2024. Environmental behaviour of synthetic and natural fibre reinforced composites: a review. In:

Advances in Mechanical Engineering, 16. SAGE Publications Inc. https://doi.org/10.1177/16878132241286020. Number 10.

Narganes-Pineda, A., González-Suárez, P., Hernández-Castellano, P.M., 2025. A definition approach to circular design for product design and development. Advances on Mechanics, Design Engineering and Manufacturing V, 309–322. https://doi.org/10.1007/978-3-031-72829-7_25.

Nordvik, E., Schütte, S., Olof Broman, N., 2009. People's perceptions of the visual appearance of wood flooring: a kansei engineering approach. For. Prod. J. 59 (11/12), 67–74. https://doi.org/10.13073/0015-7473-59.11.67.

Ortega, Z., Romero, F., Paz, R., Suárez, L., Benítez, A.N., Marrero, M.D., 2021. Valorization of invasive plants from macaronesia as filler materials in the production of natural fiber composites by rotational molding. Polymers 13 (13). https://doi.org/10.3390/polym13132220.

Palanisamy, S., Murugesan, T.M., Palaniappan, M., Santulli, C., Ayrilmiş, N., 2024. Fostering sustainability: the environmental advantages of natural fiber composite materials – a mini review. In: Environmental Research and Technology, 7. Yildiz Technical University, pp. 256–269. https://doi.org/10.35208/ert.1397380. Number 2.

Piselli, A., Baxter, W., Simonato, M., Del Curto, B., Aurisicchio, M., 2018. Development and evaluation of a methodology to integrate technical and sensorial properties in materials selection. Mater. Des. 153, 259–272. https://doi.org/10.1016/j.matdes.2018.04.081.

Rognoli, V., Bianchini, M., Maffei, S., Karana, E., 2015. DIY materials. Mater. Des. 86, 692–702. https://doi.org/10.1016/j.matdes.2015.07.020.

Santhosh, N., Praveena, B.A., Gowda, A.C., Duhduh, A.A., Rajhi, A.A., Alamri, S., Berwal, P., Khan, M.A., Wodajo, A.W., 2024. Innovative eco-friendly bio-composites: a comprehensive review of the fabrication, characterization, and applications. In: Reviews on Advanced Materials Science, 63. Walter de Gruyter GmbH. https://doi.org/10.1515/rams-2024-0057. Number 1.

Silvennoinen, J., Mononen, L., 2023. Multisensory MAYA – a Design Thinking Method to Enhance Predictability of Experience Design, pp. 308–323. https://doi.org/10.1007/978-3-031-35699-5_23.

Spence, C., Gallace, A., 2011. Multisensory design: reaching out to touch the consumer. Psychol. Market. 28 (3), 267–308. https://doi.org/10.1002/mar.20392.

Suárez, L., Castellano, J., Díaz, S., Tcharkhtchi, A., Ortega, Z., 2021a. Article are natural-based composites sustainable? Polymers 13 (14). https://doi.org/10.3390/polym13142326.

Suárez, L., Castellano, J., Romero, F., Marrero, M.D., Benítez, A.N., Ortega, Z., 2021b. Environmental hazards of giant reed (Arundo donax l.) in the macaronesia region and its characterisation as a potential source for the production of natural fibre composites. Polymers 13 (13). https://doi.org/10.3390/polym13132101.

Taekema, J., Karana, E., 2012. Creating awarness on natural fibre composites in design. International Design Conference. www.nfcdesign.org.

Thundathil, M., 2025. Designing sustainable materials: the role of material perception in consumer acceptance. New Design Ideas 9 (1), 30–59. https://doi.org/10.62476/ndi.91.30.

Urquhart, L., Wodehouse, A., 2023. Embedding perception: HOW changes in manufacturing approach influence interaction-design preferences. Proceedings of the Design Society 3, 1615–1624. https://doi.org/10.1017/pds.2023.162.

Veelaert, L., Du Bois, E., Moons, I., Karana, E., 2020. Experiential characterization of materials in product design: a literature review. In: Materials and Design, 190. Elsevier Ltd. https://doi.org/10.1016/j.matdes.2020.108543.

Wan, Q., Li, X., Zhang, Y., Song, S., Ke, Q., 2021. Visual perception of different wood surfaces: an event-related potentials study. Ann. For. Sci. 78 (2). https://doi.org/10.1007/s13595-021-01026-7.

Wastling, T., Charnley, F., Moreno, M., 2018. Design for circular behaviour: considering users in a circular economy. Sustainability 10 (6). https://doi.org/10.3390/su10061743.

Yanagisawa, H., Miyazaki, C., 2019. A methodology for extracting expectation effect in user-product interactions for multisensory experience design. Journal of Advanced Mechanical Design, Systems and Manufacturing 13 (1). https://doi.org/10.1299/jamdsm.2019jamdsm0013.

Yang, M., Jia, L., 2009. Study on Kansei engineering and its application to product design. ISCID 2009 - 2009 International Symposium on Computational Intelligence and Design 2, 525–528. https://doi.org/10.1109/ISCID.2009.277.