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DESIGNING SUSTAINABLE MATERIALS: THE ROLE OF MATERIAL PERCEPTION IN CONSUMER ACCEPTANCE

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Abstract. Material perception is vital in designing new materials and products that consumers widely accept, especially in the case of sustainable materials like biobased composites, which are unfamiliar to the average consumer. Understanding the effect of visual and tactile characteristics of the biobased composites on the formation of material perception could help material engineers and designers create sustainable and high-value materials. In this study of biobased composites, the semantic differential method is used to assess material attributes (in digital and physical settings), along with the qualitative assessment of material characteristics. These attribute ratings and qualitative descriptors help evaluate sensory qualities and generalise their influences on material perception. It is observed that respondents refer to past material experiences to define materials, especially the ones with uncertain attributes. While visual/tactile inconsistencies are a hallmark of natural products, such irregularities in materials with evidence of human interaction (e.g., weaving, geometric patterns) lead to poor perception of beauty and value. Fibreness is a strong signifier of naturality and warm and earthy tones reinforce this perception. Visual and tactile attributes influence perceptions of beauty and values, pointing to their bimodal nature; this also emphasises the role of sensory characteristics in creating desirable biobased composites.

Keywords: *Biocomposites, material design, material perception, sustainability, product design, consumer behaviour.*

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1. Introduction

Biobased composites possess sustainable credentials, reinforcing them as a viable substitute for fossil-fuel-based materials (Mohanty *et al*., 2002, Müssig *et al*., 2020). These materials are created by combining a polymer matrix with fibre reinforcement, with either or both of these components being of biobased origins, offering them better sustainability credentials. However, poor perceptual characteristics like inferior aesthetics, low value and lack of a unique visual identity professing their natural origins

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hinder the widespread adoption of these materials (Charter & Tischner, 2017; Manu *et al*., 2022; Rognoli *et al*., 2011). This results in manufacturers opting for conventional materials for their products despite the availability of sustainable materials and a way to improve the adoption of biobased composites is to solve their perceptual handicaps. Unlike biobased composites, many biobased mono-materials like wood, leather and marble possess favourable perceptual qualities due to their unique visual identity. To recreate such favourable qualities in biobased composites, the mechanism of material perception needs to be understood and the underlying factors that form the perception of biobased composites must be identified. The isolation of these core factors, in terms of correlations among perceptual qualities and the influence of material characteristics, is expected to help design new biobased composites. Identifying and understanding these factors and the relationships between underlying perceptual components helps to form a material perception framework which provides guidelines for creating biobased composites with desirable perceptions (Thundathil *et al*., 2023b).

In prior studies (Thundathil *et al*., 2023a, 2023b), various biobased material samples were analysed using the semantic differential scale in the context of both visual and visual/tactile senses. These studies have uncovered influences governing material perception in biobased composites, e.g., linked perceptual attributes and relationships between material characteristics and perceptual attributes. The approach of these preliminary explorations has been goal-oriented, explicitly focusing on uncovering attribute correlations (how one attribute relates to another) and material characteristics that affect the perception of naturality and desirability in biobased composites. From these studies, the key findings in terms of material perception in the context of biobased materials were:

- The complexity, novelty and interestingness of biobased composites correlate, pointing to the interdependence of these attributes.
- Beauty, naturality and the value of biobased composites correlate with each other; the value of these materials also correlates with perceived smoothness, simplicity and strength.
- Some factors within a value, such as perceived temperature and visual simplicity, reveal a Wundt curve correlation (inverted U-curve), signalling a medium rating in these aspects to correlate with optimum beauty and naturality.
- Beauty is a bimodal (visual-tactile) attribute, with fibrous, rhymic and harmonic visual appearances correlating with higher aesthetic perception.
- Naturality is correlated with visual and tactile aspects such as warm colours, organic patterns, fine texture and visually harmonic elements.
- Value depends more on tactility, with characteristics such as smoothness, hardness, visual consistency, sensory simplicity, high aspect ratio fibres and ordered patterns correlating with higher valuations.
- Factors like beauty, interestingness and agedness depend on visual cues and tactility has less effect on these attributes.

These findings contributed to a material perception framework (Thundathil *et al*., 2023a) in the context of the naturality and desirability (beauty and value) of biobased composites. Defining these qualities as absolute values is challenging (Day & Crask, 2000; Wong *et al*., 2021; Zeki, 2019), but they represent a universally accepted nomenclature for defining emotionally similar sensations. Beauty in the context of this study represents a materialistic quality, consisting of both sensorial pleasantness and aesthetics. It is considered an objective or independent quality and is defined as the collective result of various sensory inputs (Zangwill & Hinton, 2020). It is regarded as a primarily visual but bimodal experience with attractive, interesting and pleasing qualities. Beauty is closely linked to desire (Zeki, 2019) and along with value, forms desirability. Value is defined here as the valorisation of a material due to its functional and emotive qualities. A material could be considered valuable due to its beauty (Palmroth, 1991) and functional qualities like superior mechanical properties or usefulness (Kelly, 1995) and it could be regarded as valuable due to the worth assigned to the material due to its social context (Gilly *et al*., 1992; Holbrook, 2012). Naturality is defined as the perceptual quality of being associated with natural agents and processes. This association means the presence of natural elements (e.g., fibres and crystals), organic patterns seen in nature (wood grains, marbling) and evidence of life (signs of growth, life and death). Naturality is often associated with positive emotions and is hence considered desirable for consumers (Karana, 2012; Rozin, 2005). These definitions of perceptual qualities (beauty, value and naturality) discussed above and their subsequent referrals in this paper are limited to the context of biobased materials and product design and are not intended to be generalised.

There are certain constraints under which earlier studies (Thundathil *et al*., 2023a, 2023b) into biobased composite perception are structured, which needs to be considered while extrapolating the outcomes onto predicting perceptions of biobased composites in general. One aspect is that the number of biobased material samples used in the earlier studies is limited. While these materials represent the most common composite types and their visual attributes, they cannot be considered to include all types of visual and tactile characteristics. Another aspect is that the attribute scales used to describe and rate the material samples were drawn from prior literature (Osgood & Suci, 1955; Trofimova, 2013) and were shortlisted by the research team. There might also be additional attributes that are more apparent to the average consumer or the ones that were included in prior studies but found irrelevant.

Further qualitative explorations on material perception are required to examine the effects of these limitations and test the current hypothesis about the influence of visual characteristics and critical attributes in forming a perception. The main objectives of this study were to examine the selection of attributes and test outcomes from prior research and thus extend the understanding of consumer perception of biobased composites. This examination required testing the assumptions about attribute-attribute correlations and material characteristic-perception correlations using a set of commercially available biobased composites and using a more qualitative approach in attribute (using descriptors) selection.

The research questions that were addressed are:

• Does the attribute selection of the researchers correspond with the primary verbal descriptors used by consumers? Do the selected attributes represent the breadth of perceptual attributes (or material descriptors) suggested by the consumers? This would help identify the critical attributes in perception formation and narrow the focus for future studies.

• What are the material characteristics that influence various perceptual associations? What are the effects of visual and tactile characteristics on the perception of beauty, value and naturality? This examines the broader applicability of the design framework from Thundathil et al. (2023a) for biobased composites in general.

Comparing the results from this study with assumptions made from prior literature will test the validity of these assumptions. This will also help examine the attributes used from a user-centric perspective and strengthen the selection of adjectives/ descriptors.

2. Methodology

This study used eight biobased composite samples and one non-biobased composite (glass fibre fabric-reinforced epoxy resin) as a benchmark. These materials were selected to represent the span of commonly available biobased composite material types used in manufacturing consumer products and the number of samples was limited to nine to avoid survey fatigue among participants. These samples were each 50 mm x 50 mm in size and their images are provided in Figure 1. The following is a short description of the production and origin of the composite materials used:

1. Coir (Coir/epoxy): Coir fibre bundles (*Cocos nucifera L.*) were aerodynamically flat laid; 30% by mass of fibres processed with epoxy resin in a compression moulding process to produce the composite.
2. Cordenka (Cordenka/polypropylene): Plain weave fabrics (295 g/cm^2) made of Rayon yarn (Cordenka GmbH & Co. KG, Oldenburg, DE); compression moulded with polypropylene at a fibre volume content of 50%.
3. Flax FE (Flax/epoxy): Flax (*Linum usitatissimum L.*) fabric (twill weave, 360 g/m^2, GreenBoats GmbH, Bremen; compression moulded with biobased epoxy resin at a fibre volume content of 47%; a commercial product of the company Greenboats GmbH (Bremen, DE).
4. Flax FT (Flax/epoxy): Flax (*Linum usitatissimum L.*) fabric (plain weave, 380 g/m^2) processed into composite material (fibre volume content of 31%) using vacuum infusion and epoxy resin (NPSP, Amsterdam, Netherlands).
5. Flax UT (Flax/epoxy): Flax (*Linum usitatissimum L.*) unidirectional textile (0°/90°); compression moulded with biobased epoxy resin at a fibre volume content of approximately 50 % (Greenboats GmbH, Bremen, DE).
6. Glass Fibre (Glass fibre/epoxy): Glass fabric (twill weave) processed into composite material using vacuum infusion and epoxy resin (NPSP, Amsterdam, Netherlands).
7. Hemp (Hemp/epoxy): Hemp (*Cannabis sativa L.*) needle felt (field-retted hemp) at 1100 g/cm^2 processed into composite material (fibre volume content of 16%) using a vacuum injection process and epoxy resin (NPSP, Amsterdam, Netherlands).
8. Jute (Jute/epoxy): Jute (*Corchorus capsularis L.*) needle felt processed into composite material (fibre volume content of 17%) using a vacuum injection process and epoxy resin (NPSP, Amsterdam, Netherlands).
9. Sisal (Sisal/ polypropylene): Leaf fibre bundles of the sisal plant (*Agave sisalana P.*) were used to manufacture the natural fibre-reinforced injection moulding polypropylene compound (fibre mass content of 30%); design study by the Ford company, Aachen, Germany (Richter *et al*., 2010).

The thickness of the above material samples varied from 2 to 8 mm owing to the origin of material samples from different sources. All the materials were rigid to human touch and all the sample surfaces, barring the top, were covered to avoid any biases emanating from observing the cross-section of the materials. None of the samples had any discernible smell, which could have impacted the perceptual assessments. In contrast with the materials used in prior studies referenced in the preceding section, which included organic and rhymic patterns (distinct repeating features with some common elements) (Thundathil *et al*., 2023b), all the current samples had chaotic (e.g., random fibre orientation) or ordered fibre reinforcement (e.g., woven or unidirectional fibres), which is prevalent for commercial biobased composites. None of the materials had a rhymic visual appearance that correlates the most with natural materials (e.g., wood grains) and the one unidirectional composite sample (Flax UT) resembled woven fabric due to the biaxial orientation of layers.

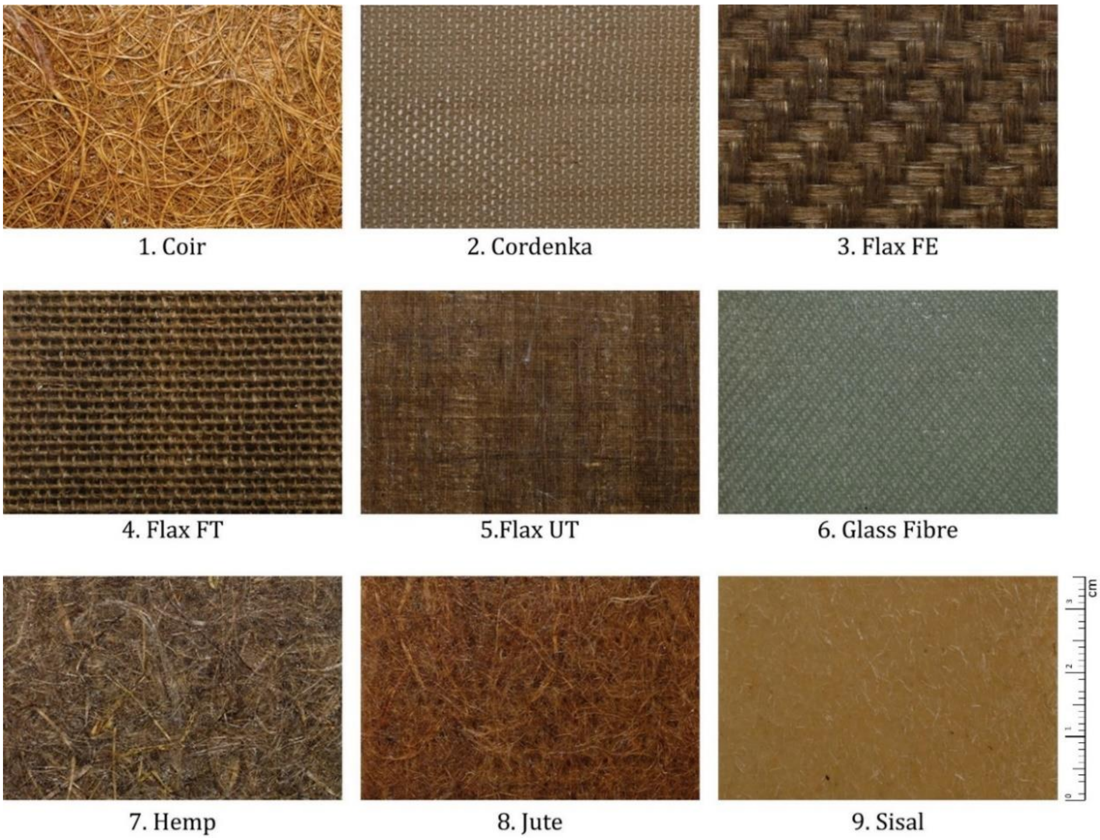

Figure 1. Images of composite samples used in the study

This study was conducted amongst 28 undergraduate students from the HSB - City University of Applied Sciences, Bremen, as part of a workshop on material perception. The study had two sessions - (i) Visual and Visual-Tactile (physical) perception and (ii) Qualitative assessment of material samples.

In the first session, students were divided into six groups and out of these, three groups (15 students in total; ten females, five males) were assigned visual testing where they evaluated the materials based solely on their photographs presented on a screen. The median age of participants in this group was 21 and the median duration for assessment was 14 minutes and 10 seconds. No physical material samples were handed to this group for material ratings to avoid tactile influence. The remaining participants (13 students, eight females and five males) were given the physical material samples to rate them so that the tactile signals become a part of their material perception. The median age of participants in this group was 22 and the median duration for assessment was 11 minutes and 30 seconds. The students from both groups (visual and visual-tactile) rated the materials on a Likert Scale delivered through the QUALTRICS online survey platform.

Participants were asked to rate each material on eight bipolar attribute scales: *Complex–Simple, Interesting–Boring, Natural–Artificial, Unusual–Ordinary, Beautiful–Ugly, Valuable–Worthless, Strong–Weak* and *Rough-Smooth*. Each attribute scale had five rating options with similar gradations; e.g., the five options for the *Complex–Simple* scale were *'Definitely Complex', 'Looks Like Complex', 'Can't say', 'Looks Like Simple'* and *'Definitely Simple'*. Due to the small sample size, statistically significant correlations could not be established and only fundamental comparative statistical analyses using medians and averages were conducted. The percentage of favourable ratings against each attribute was computed by combining the rating frequency of *'Definitely'* and *'Looks Like'* ratings against each attribute.

In the second session, all student groups (same students from the prior session) were presented with physical biobased composite samples and were asked to discuss and identify characteristics affecting their perception of these materials. Students were asked to scrutinise various visual and tactile features of biobased composites and introspect how their variation affects their perception of the materials. Each student group was then asked to list a set of attributes or descriptors they found suitable to describe each material sample, resulting in 6 sets of descriptors for each material sample. However, only three out of six groups submitted documentation for descriptors, limiting the generalisation of outcomes. Since the task was group-based, there might be some biases or influences by peers in outcomes; the highly assertive members may also influence the descriptor selection in each group. This qualitative data was analysed for synonymous attributes/descriptors and then all such adjectives were combined into the nearest attributes (e.g., descriptors such as *ugly*, *unappealing*, *disturbing*, *dirty* and *disgusting* were generalised as *Ugly*). This list of attributes against each material was illustrated using a word cloud generated using www.wordclouds.com. The most frequently used adjectives were represented in the largest font and font size decreased progressively with lower frequency; this revealed the significant attributes associated with each material.

3. Results & Discussion

3.1. Material Assessments

In discussions, the participants used various descriptors and adjectives to describe materials and their qualities (Figure S3 in Supplementary Materials). These descriptors form the semantic space and in conjunction with general rating trends, give more profound insights into the formation of material perception. The semantic spaces constructed for each composite sample are discussed below:

3.1.1. Coir

In this study, *Coir* had similar ratings among visual and visual-tactile assessment modes and was rated highly in beauty and naturality on the Likert scale. *Coir* also generated strong conflicting opinions (Figure 2) with many descriptors such as *"aesthetically interesting", "visually appealing", "pleasant colour"* and *"exciting"* used along with polar adjectives such as *"ugly"* and *"repulsive"*. This conflict in perception is also seen in ratings, where Coir had a significant shift in perception in visual-tactile mode. Coir also evoked descriptors associated with complexity and interestingness, such as *"chaotic", "restless", "unordered"* and *"multidimensional"*. The correlation between complexity and beauty (as a measure of material preference) has been observed in earlier studies (Berlyne, 1971; Friedenberg & Liby, 2016; Thundathil *et al*., 2023a, 2023b). Berlyne (1971) also suggests a negative correlation between complexity and preference at high levels of complexity; the chaotic yet long continuous fibres found in the samples might create an optimum level of complexity, with woven fibre composites at low complexity and short random fibres at high complexity. This orientation may have also led to a comparatively positive aesthetic assessment of the material despite a few unfavourable evaluations.

Figure 2. Image of the Coir sample and the adjective word cloud generated for Coir

There was uncertainty in assessments for *Coir* (indicated by multiple descriptors such as *"confusing", "uncertain"* and *"uncertainty"*), presumably due to the visual-tactile complexity. In such a scenario, assessments could heavily depend on the emotional and cultural associations of the participants. In this case, the material was described as *"spaghetti"* and *"worms-like"*, which could be considered visually similar but perceptually distant in a general sense. The organic and visually significant nature of coir fibres created a strong sense of naturality as well, illustrated by comparisons to visually similar natural elements *("straw-like", "straw", "stems"*) and *"natural"* descriptors appearing multiple times in the discussion.

3.1.2. Cordenka

Cordenka was perceived as artificial, worthless and ugly on the Likert scale, which was also reflected in the comments by the participants (Figure 3). A key characteristic observed by the participants was the weave of the Cordenka fabric and the monotony of its visual order *("ordered", "symmetric", "regular"* and *"weave"*). Visual monotony and order led to unappealing aesthetics (*"not visually appealing"* and *"dislike"*) and a lack of value and interest in the materials (*"cheap", "boring"* and *"simple"*). This visual order and resultant simplicity lead to low interest and poor preference (Aitken, 1974). The ordered nature of the fabrics also indicated artificiality to the participants (*"artificial-processed structure of high fineness"*) and also led to emotional/cultural associations with products based on visual attributes (*"porous", "airy"* and *"parents' sofa"*).

Figure 3. Image of the Cordenka sample and the adjective word cloud generated for Cordenka

3.1.3. Flax FE

Flax FE was rated favourably by the participants (Figure 4), with an appreciation of aesthetics (*"most beautiful image", "pretty nice", "visually appealing"* and *"highest quality"*). This material also had a mix of naturality (fibres and visual inconsistencies) and artificiality (*"symmetric", "harmonic", "ordered"* and *"structured"*), prompting a participant to describe this material as *"unnatural"* and *"somewhere in the middle between processed and natural"*. The visual inconsistency caused by the uneven colour of flax fibres also caused the perception of ageing in the material. This processing intervention (weaves) and prolonged use (ageing) also anchored user perception onto the product context from their cultural associations (*"grandma with a shopping basket"* and *"old weathered garden chairs"*). It is also interesting to note that with signs of human intervention in material processing (e.g., weaves), the respondents compared the images with visuals in their memory to create an assessment. This assessment outcome could thus be a result of visual stimuli and personal experiences (Jacobsen *et al*., 2006).

Figure 4. Image of the Flax FE Sample and the Adjective Word Cloud Generated for Flax FE

The balance of order with complexity and interestingness arising from visual inconsistency (aged feel) generated a perception of timelessness ("old fashioned & modern"). The material had visual roughness but was tactilely smooth, adding to the pleasurable experience due to conflicting sensory inputs (Ludden *et al*., 2012).

3.1.4. Flax FT

Flax FT had high ratings for strength and value; this high value can be considered functional value from the perception of strength. Interestingly, this material has a high perception of roughness (Figure 5), arising primarily from its visual attributes (*"cat scratching post", "rough-fibrous", "scratchy", "doormat"* and *"very, very rough"*); however, the actual roughness (tactile) is much lower than expected (Figure S1 and Figure S2 in Supplementary Materials). This observation aligns with the hypothesis that surface smoothness is associated with material strength (Thundathil *et al*., 2023a), contributing to strength perception despite the attribution of roughness. This material thus illustrates the primacy of tactility over vision in forming strength perception. This smoothness, along with the ordered geometric pattern (*"symmetric", "ordered composition"* and *"structured"*), enhances the strength perception, prompting participants to use descriptors such as *"durable", "robust", "indestructible"* and *"higher quality"*.

Another aspect is the relative thickness of warps and wefts in flax samples (Flax FE & Flax FT) compared with other woven samples; this higher thickness also contributes to the perception of durability and strength. However, the inconsistency in colour may be contributing to a worn perception (*"old silk", "old"* and *"dirty"*).

Figure 5. Image of the Flax FT Sample and the adjective word cloud generated for Flax FT

3.1.5. Flax UT

Flax UT had unfavourable ratings against value and strength (Figure 6); one reason for this may be the visual inconsistencies on the surface that were highlighted by the participants using terms such as *"scratched", "not well coated/something went wrong", "damaged worktop"* and *"not refined"*. Another reason may be that this sample had a lower thickness than others. This would explain the significant change in strength perception in the visual-tactile mode compared to the visual mode (Figure S5 in Supplementary Materials). The perception of strength in visual mode may be attributed to the structured look, not by virtue of weave, but due to the superimposition of two biaxially-oriented unidirectional layers of flax (*"longitudinal/horizontal stripes", "finely meshed"*).

The inconsistencies in visual properties, such as colour variation observed for flax fibres, also contribute to the perception of wear as well as ugliness (*"ugly", "not aesthetic", "dirty"* and *"dirty papyrus"*). It is worthwhile to note that while visual unevenness is considered an inherent attribute of natural materials, such unevenness in artificial objects is regarded as a flaw or functional defect. This is also because, for industrial-made (artificial) materials, consistency is a crucial indicator of quality. Beyond artificiality, familiarity with similar objects also leads to this heightened dislike of inconsistencies; a good example is consumers' poor perceptual preference towards misshapen agricultural produce (Yuan *et al*., 2019).

Figure 6. Image of the Flax UT sample and the Adjective Word Cloud Generated for Flax UT

3.1.6. Hemp

Hemp had a high rating for naturality, which was correlated with a series of natural-origin descriptors such as *"natural", "mixture of a cow pad and straw pressed together", "squashed horse manure", "swamp", "forest floor"* and *"moss"*, evident in the word cloud (Figure 7). However, these had negative associations in the case of visual aesthetics as well. The complexity and unevenness of hemp fibres in the resin matrix (*"inhomogeneous composition", "uneven", "pressed together"* and *"three-dimensional impression"*) led to a conflicting assessment of roughness, with the material assessed as rough in visual mode to a higher smooth assessment in visual-tactile mode (Table S1 and Table S2 in Supplementary Materials).

Figure 7. Image of the Hemp sample and the adjective word cloud generated for Hemp

3.1.7. Jute

Jute was one of the materials with high ratings for naturality, beauty and interestingness, which was also reflected in its descriptors (Figure 8). Tactility also affected *Jute*, as it had perception changes (between digital and physical modes) for all attribute scales, barring *Natural-Artificial*. The descriptors seen for *Hemp* regarding the homogeneity were also seen here, with participants using descriptors such as *"fluffy (not densely packed)", "pressed together", "inhomogeneous structure"* and *"felt-like"*. Jute also exhibited some sensory dissonance for the *Rough-Smooth* scale, with it being rated as *'Definitely Rough'* in visual mode to *'Looks like Soft'* in visual-tactile mode (Table S1 and Table S2 in Supplementary Materials).

The participants strongly emphasised the naturality of the material by using a range of natural references to illustrate this quality *("forest", "roots", "Redwood Forest", "fine roots"* and *"natural"*). Interestingly, *Jute* had a higher assessment of beauty in the visual-tactile mode, pointing to the impact of tactility here. Some participants expressed surprise when examining the material (*"actually not ugly at all", "pleasant to look at", "colour is nicer"* and *"visually appealing"*). While *Jute* is very similar to the hemp composite in fibreness, the effect of colour seems to have made a strong impression on the perception of beauty. This preference for warm-toned materials may be analogous to consumer preference for dark brown shades of wood over pale ones (Preklet *et al*., 2019). The impact of tactility was higher on the *Rough-Smooth* scale, with the material being rated smoother in visual-tactile mode; this improvement in smoothness also led to a higher appreciation of strength (Figure S2 in Supplementary Materials).

Figure 8. Image of the Jute sample and the adjective word cloud generated for Jute

3.1.8. Sisal

Sisal (injection moulded part with short sisal fibres and fibre bundles) was rated very poorly across most attribute scales, but the participant reaction towards this material was very enlightening, underscoring the requirement for material perception studies (Figure 9). This material evoked strong adverse reactions regarding the material, such as *"really ugly", "nothing cool", "shock frosted vomit"* and *"disgusting"*. The presence of polypropylene as the matrix polymer lends some translucent effects in fibre dispersion and the pale colour of sisal fibres accentuates this. Both of these aspects might have led to negative perceptual associations. This material was also associated with personal associations with aged and worn analogues such as *"old-fashioned tiles", "really old, worn, f*cked up floor of a sports hall/gym"* and *"ugly linoleum floor"*. This material had a smooth perception, which was usually associated with strength in earlier studies (Thundathil *et al*., 2023a), but the short fibres (*"white fuzz"*) were detrimental to this. These randomly oriented short, pale and fine fibres may have given the impression of wear and thus negatively impacted the aesthetics (*"white fuzz is unappetising"*).

This outcome is very illuminating, as this sample was initially considered for use in automotive interiors (Richter *et al*., 2010) and such negative material perception could have significantly impacted product acceptance.

Figure 9. Image of the Sisal sample and the adjective word cloud generated for Sisal

3.1.9. Glass Fibre

Glass Fibre was an exception in the sample set, prepared from non-biobased materials and was selected to represent a common non-biobased composite material. It was used as reference material to test the accuracy of participants in assessing naturality and to compare its perceptual qualities with those of biobased composites. *Glass Fibre* went from one of the smoothest rated materials in visual-only mode to one of the roughest rated materials in visual-tactile mode, illustrating the dissonance between visual and visual-tactile assessments. Participants used both "rough" and "soft" to describe the materials and a perceptual shift is evident (Figure S4 in Supplementary Materials). This material had a micro-roughness quality, as Okamoto et al. (2013) defined, which might be causing the conflicting assessments. The descriptors associated with woven patterns (*"finely meshed", "structured", "fine weave"* and *"woven"*) have contributed to the relatively high strength assessment for *Glass Fibre*. At the same time, this results in artificiality, expressed correctly by the participants as *"processed", "not natural"* and *"unnatural"*.

The colour of this material was unique, with a blueish-green tone differentiating it from the other earth-toned composites in this study. This was considered unpleasant by many participants (*"ugly", "not an appealing colour", "disturbing"* and *"dirty"*). The lighter shade also gave a worn feel to the participants (Figure 10), which in turn evoked the feeling of a functional material (*"older carpet", "worn seat cover in the Berlin tram", "picnic blanket"* and *"work jacket"*). This material fared poorly on crucial attributes such as beauty, naturality and value, thereby revealing an opportunity for biobased composites to substitute glass fibre-reinforced composites, especially in consumer interfacing products.

Figure 10. Adjective Word Cloud Generated for Glass Fibre

3.2. Attribute Assessments

While the perceptual ratings against each material-attribute combination can be explained with descriptive assessments, the same approach could be applied to the focus attributes in this study (naturality, beauty and value). Combining the descriptors from the highest-rated materials in each attribute class (Table S3 and Table S4 in Supplementary Materials) can uncover common characteristics that link these materials.

3.2.1. Naturality

The change in perception of naturality has been minimal when comparing the visual-only (digital-visual) and the visual-tactile (physical) modes of assessment (Figure 11). While naturality has been observed as tactilely dominant in diverse material samples (Thundathil *et al*., 2023a), the tactile variations in the current sample set have been limited, compelling the participants to rely more on visual cues. It has been observed that the visual, tactile and visual-tactile assessments correlate in the case of materials samples with similar characteristics (e.g., woods, wood substitutes and wood replicas) (Overvliet & Soto-Faraco, 2011), which might also be the case here. It was observed that the glass fibre-reinforced composite (*Glass Fibre*), used as a benchmark for artificiality, was accurately identified by the participants in visual and visual-tactile modes. It is also interesting to note that *Cordenka*, which consists of regenerated cellulose fibres, was rated as more artificial than the rest of the biobased materials, pointing to the lack of visual cues that could have helped this material to project its biobased origin. This also illustrates that processing intervention and visual consistency may act as a contagion and deprive natural materials of their identity (Rozin, 2005). *Coir*, *Jute* and *Hemp* were rated as the most natural materials in the group and this could be due to their high fibreness and lack of visual order.

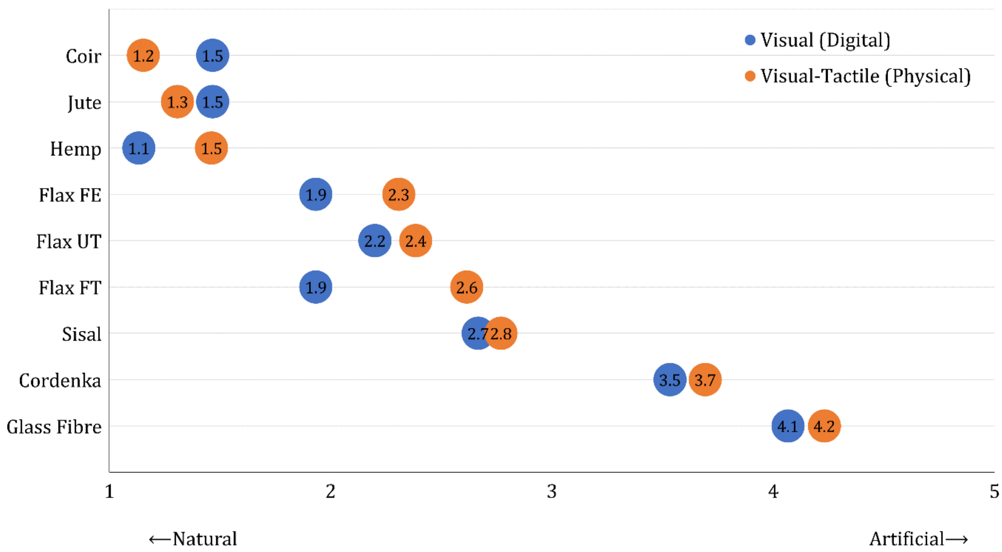

Figure 11. Comparison of Average Ratings on the Natural-Artificial Scale in two modes of assessments

The descriptor word clouds were compared for materials with the highest ratings in *Natural (Coir, Hemp & Jute)* and *Artificial (Glass Fibre, Cordenka)* to correlate the visual-tactile characteristics with the perception of naturality (Figure 12). In the current sample context, fibrous (splintery, felt, three-dimensional fibres) or heterogeneous (distinct presence of matrix and reinforcement materials) was a common descriptor for natural-perceived materials. This attribute has been observed previously (Thundathil *et al.*, 2023b), strengthening this observation. Natural materials have been correlated with beauty in earlier studies; however, natural materials in this context (random fibres, chaotic characteristics) were perceived to have a displeasing appearance, evident from the term *'ugly'* used to describe these materials in some cases. This reinforces the hypothesis from Thundathil et al. (2023a, 2023b) that while fibrous correlates with naturality, the visual rhyming (or pattern) of these fibres dictates the perception of beauty.

Inversely, artificial materials also had a clear presence of fibres but in a very ordered (e.g., woven) format, which is less common for natural materials. These materials were also generally rated as boring and not beautiful, presumably due to the ordered visual structure. While roughness was an attribute that correlated with naturality, it is noted here that materials like *Glass Fibre* and *Cordenka* had high ratings for roughness but failed to evoke naturalness. This illustrates that visual cues (such as fibre order and evidence of processing) are still relevant as a marker for perceiving naturality.

Figure 12. Comparison of Word Clouds for Materials Rated Highly for Natural and Artificial

3.2.2. Beauty

The study participants generally rated the samples more beautiful when they assessed them in the visual-tactile mode than the visual-only mode (Figure 13). Ernst and Banks (2002) notes that in the case of bimodal perception, the sensory input with lower variance becomes dominant over the input with a higher variance; i.e., consistent sensory stimuli lead to confident decisions, which in turn dominates the overall perception. The tactile variance is lesser in the current samples, which might have provided enhanced significance to tactility in visual-tactile mode. Another reason for this better assessment of beauty may be the higher perceived smoothness in visual-tactile mode and people find smooth surfaces more pleasurable (Etzi *et al.*, 2014). Amongst the samples, only *Cordenka* and *Glass Fibre* were rougher in visual-tactile mode (Figure S4 in Supplementary Materials), which explains the lack of improvement in the perception of beauty in visual-tactile mode. This also aligns with the argument that aesthetic appreciation is influenced by both vision and touch (Jansson-Boyd & Marlow, 2007). *Coir* and *Flax FE* were rated the most natural materials, while Cordenka, Flax UT, Hemp and Sisal were rated the ugliest.

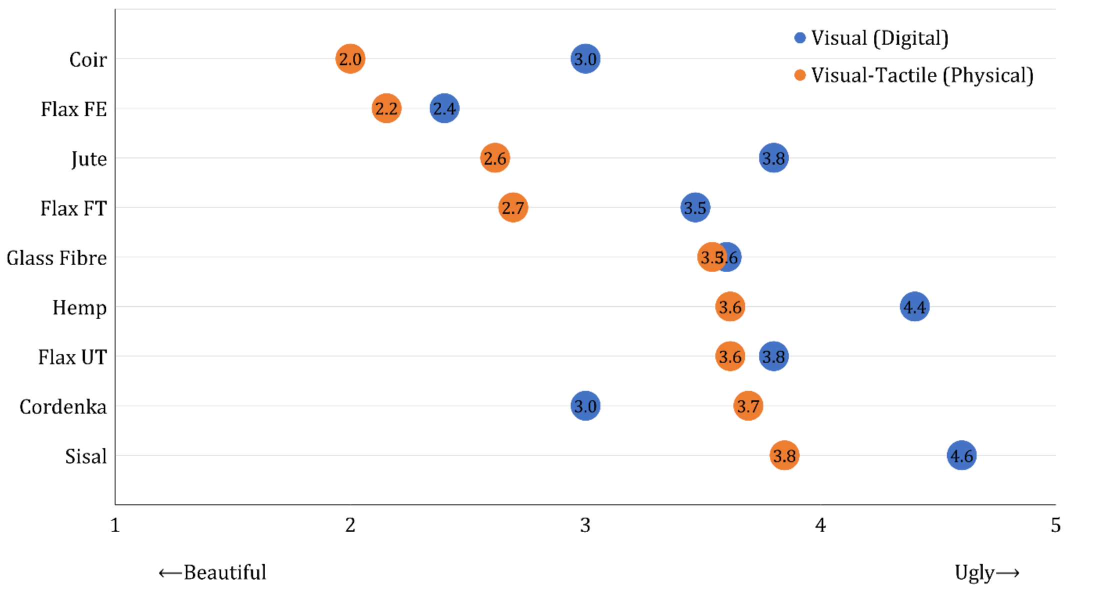

Figure 13. Comparison of Average Ratings on the Beautiful - Ugly Scale in Two Modes of Assessments

The word cloud comparison for beautiful and ugly materials is illustrated in Figure 14. A visual contrast of high-beauty materials demonstrates the role of complexity in the perception of beauty. While *Flax FE* is ordered, its complex weave pattern also has an inconsistent fibre appearance, thereby adding to its visual complexity; this material is also rated the smoothest, making it pleasurable in a tactile context. *Coir* is rated rough in this context, but the perception of beauty here comes from the high perception of naturalness and visual complexity of long fibre bundles. The randomness and chaotic nature of fibre orientation may influence a few *'ugly'* descriptors, but the interestingness of the material compensates for these negative attributes.

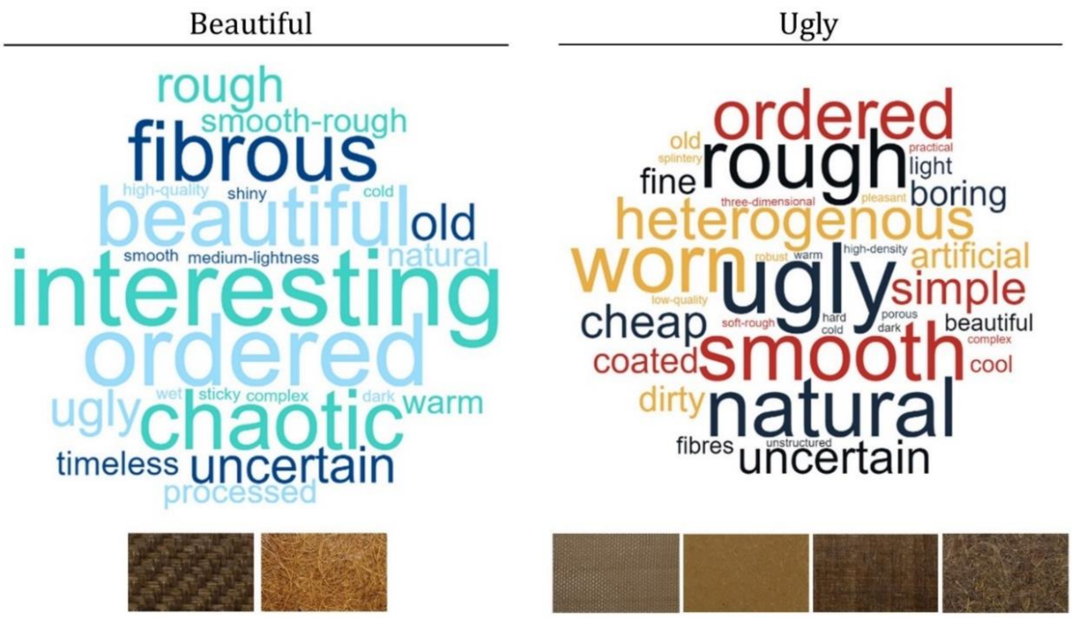

Figure 14. Comparison of Word Clouds for Materials Rated Highly for Beautiful and Ugly

The common characteristics of the perceived-ugly materials were visual simplicity imparted either by highly ordered patterns or random short-fibre arrangements. This outcome may infer that while the randomness of long fibre bundles leads to interesting perception, the complexity of short-fibre interfaces fails to produce any such emotion.

3.2.3. Value

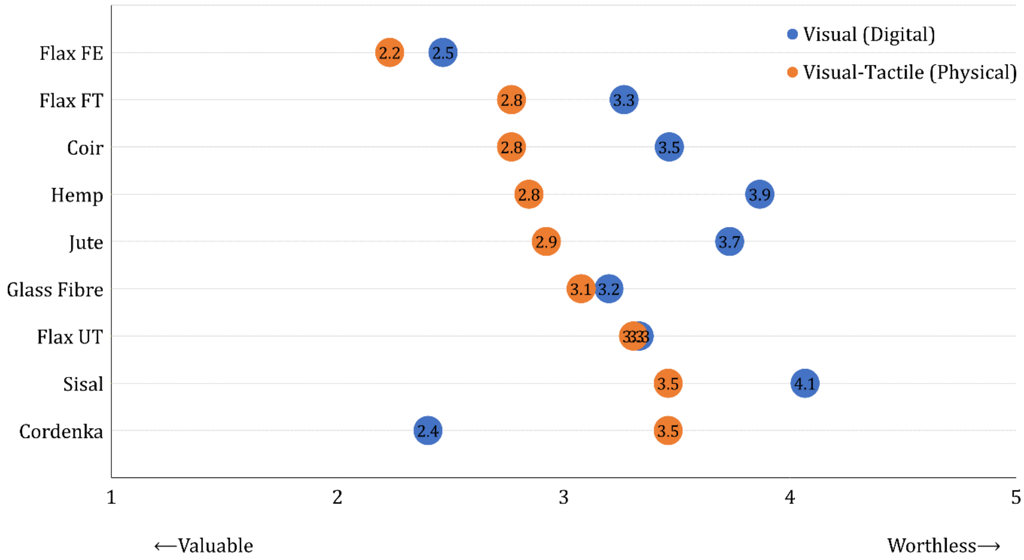

Figure 15. Comparison of Average Ratings on the Valuable-Worthless Scale in Two Modes of Assessments

The positive correlation between beauty and value in biobased composites has been established in Thundathil et al. (2023a) and this trend is also observed here. Analogous to improved perception of beauty in visual-tactile mode, there has also been a shift towards higher value for materials. The aberration to this is *Cordenka*, but this could be attributed to the surface inconsistencies of this material when observed closely in visual-tactile mode. The highest-valued materials in the group were *Flax FE* and *Flax FT* (Figure 15). It has been observed that materials derive their perception of value from both aesthetic and functional values; *Flax FE* has a good combination of beauty (rated second) and strength (rated first), whereas *Flax FT* draws more from strength (rated first) and less on beauty (rated fourth) (Table S4 in Supplementary Materials). While the woven patterns of the fibre reinforcement significantly contribute to the perception of strength, the additional perception of beauty enabled these materials to be valued more than similar materials with fabric reinforcement. Doyle (2009) describes four aspects of the perception of value, namely (i) functional value, (ii) financial value, (iii) social value and (iv) psychological value, which correlates with Maslow's (1943) hierarchy of human motivation, where functional needs are considered more fundamental and essential than psychological and social needs. It could be argued that while functionality and aesthetics contribute to material value, functional expectations from the biobased composite (e.g., strength, durability) may take precedence over emotional expectations (aesthetics, social value), forming the basal attribute for the perception of value. It should also be noted that some material samples had variations in thickness due to processing limitations, with *Jute* being the thickest (6.6 mm) and *Flax UT* being the thinnest (0.9 mm). This might have influenced the perception of strength in the visual-tactile mode for these materials.

The inverse of the abovementioned factors is seen in materials deemed most worthless (*Cordenka and Sisal*). While *Cordenka* has a woven reinforcement, its visual inconsistencies in weaves and boring interface adversely affected its perception of value; in the case of *Sisal*, a combination of random short fibres and poor beauty ratings led to its worthless perception. These findings align with the desirable biobased composite perception framework, as detailed in (Thundathil *et al*., 2023a).

Figure 16. Comparison of Word Clouds for Materials Rated Highly for Valuable and Worthless

While looking at the descriptors used to illustrate the most valuable (*Flax FE & Flax FT*) and worthless (*Cordenka & Sisal*) materials (Figure 16), the aspects discussed above are observed here as well. The impact of beauty and functional value is evident for the valuable materials. *Flax FE* is rated highly in the aesthetic features, combined with the strength perception derived from the woven yarn (ordered fibres). *Flax FT* has more naturality descriptors (natural, rough, complex) along with functional descriptors (ordered, durable), which makes up for the poor perception of beauty in this material (rated fourth in beauty). This impact of visual cues is evident in *Cordenka*, where its positive functional descriptors (ordered, simple) should have improved its value perception. However, it is let down by negative attributes (uncertain, boring, ugly), effectively reducing the overall value of the material.

4. Conclusion

This study shows that the critical values required for an ideal biobased composite (naturality, beauty and value) are linked; physical material characteristics like fibreness, visual consistency and smoothness are also seen to strengthen these attributes as hypothesised. The impact of dominant tactile qualities such as roughness/smoothness on material perception is apparent in this study. The significant perceptual dissonance between visual assessment and visual-tactile assessment for many material-attribute combinations suggests that there could be a large gap between consumer expectations formed through visual media and actual product experiences. This is very relevant in the case of e-commerce and could help enterprises represent the products better visually or use supplementary information/interface to accurately communicate the actual material/product experience.

The impact of tactility has been significant in assessing beauty and value in this study. This also revealed the dominance of tactility when the variance in tactile stimuli is less than that of the visual variance. It implies that the dominance of senses (visual or tactile) in product experiences could be controlled by regulating their variances. This could also help confine consumer perception to only certain material aspects. For example, if a material has uneven surface patterns or colours, this could be highlighted with an uneven texture and vice versa; an even surface texture will downplay the visual inconsistencies.

Another focus of this study was on the qualitative aspects of the material assessment, observed through applying descriptors for each material. The main observation was that respondents did not use all the key attributes to describe materials. Beyond visual-tactile attributes, most of the descriptors used were rooted in personal contexts (product usage scenarios) and functional attributes (e.g., durable, strong). This effect was more substantial and evident in materials with clear evidence of human manipulation. This might also indicate that the core values explored in this study (naturality, beauty and value) may be implicit, subconscious and not always visible and explicit. While these attributes may not be apparent unless specific queries are posed against them, the cumulative impact of these attributes seems to be crucial from the material rating data for the same group of respondents. Further qualitative studies using semi-structured interviews with design professionals may help reveal the influence of the core attributes and material characteristics in forming material perception in biobased composites.

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Ethics approval

This study was approved by the Legal department of HSB-City University of Applied Sciences Bremen, Germany (declaration dated 24.01.2023).

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Supplementary Materials

Table S1. Median Attribute Assessment for each material-attribute combination (Visual Only)

	Rough - Smooth	**Beautiful - Ugly**	**Interesting - Boring**	**Unusual - Ordinary**	**Valuable - Worthless**	**Complex - Simple**	**Strong - Weak**	**Natural - Artificial**
Coir	Definitely Rough	Looks Complex	Looks Interesting	Definitely Natural	Looks Unusual	Can't Say	Looks Worthless	Can't Say
Cordenka	Can't Say	Looks Complex	Looks Interesting	Looks Artificial	Can't Say	Can't Say	Looks Valuable	Looks Strong
Flax FE	Looks Rough	Looks Complex	Looks Interesting	Looks Natural	Can't Say	Looks Beautiful	Looks Valuable	Looks Strong
Flax FT	Definitely Rough	Looks Complex	Can't Say	Looks Natural	Looks Ordinary	Looks Ugly	Can't Say	Looks Strong
Flax UT	Looks Rough	Can't Say	Looks Boring	Looks Natural	Can't Say	Looks Ugly	Looks Worthless	Looks Strong
Glass Fibre	Can't Say	Can't Say	Can't Say	Looks Artificial	Can't Say	Looks Ugly	Looks Worthless	Looks Strong
Hemp	Definitely Rough	Looks Complex	Looks Boring	Definitely Natural	Can't Say	Definitely Ugly	Looks Worthless	Can't Say
Jute	Definitely Rough	Can't Say	Can't Say	Definitely Natural	Looks Unusual	Looks Ugly	Looks Worthless	Looks Weak
Sisal	Looks Smooth	Looks Simple	Looks Boring	Looks Natural	Can't Say	Definitely Ugly	Looks Worthless	Can't Say

Table S2. Median Attribute Assessment for each material-attribute combination (Visual-Tactile)

	Rough - Smooth	Beautiful - Ugly	Interesting - Boring	Unusual - Ordinary	Valuable - Worthless	Complex - Simple	Strong - Weak	Natural - Artificial
Coir	Definitely Rough	Looks Complex	Interesting	Definitely Natural	Can't Say	Looks Beautiful	Can't Say	Can't Say
Cordenka	Looks Rough	Can't Say	Can't Say	Looks Artificial	Looks Unusual	Looks Ugly	Looks Worthless	Looks Strong
Flax FE	Definitely Smooth	Looks Complex	Looks Interesting	Looks Natural	Can't Say	Definitely Beautiful	Looks Valuable	Looks Strong
Flax FT	Looks Smooth	Can't Say	Can't Say	Looks Natural	Can't Say	Looks Beautiful	Can't Say	Looks Strong
Flax UT	Looks Rough	Can't Say	Looks Interesting	Looks Natural	Can't Say	Looks Ugly	Can't Say	Looks Weak
Glass Fibre	Definitely Rough	Can't Say	Can't Say	Looks Artificial	Looks Unusual	Looks Ugly	Can't Say	Looks Strong
Hemp	Can't Say	Looks Complex	Looks Interesting	Definitely Natural	Can't Say	Looks Ugly	Can't Say	Can't Say
Jute	Looks Smooth	Looks Complex	Looks Interesting	Definitely Natural	Can't Say	Looks Beautiful	Can't Say	Looks Strong
Sisal	Definitely Smooth	Looks Simple	Can't Say	Can't Say	Looks Unusual	Looks Ugly	Looks Worthless	Can't Say

Table S3. Favourable ratings for each material against various attributes (Visual Only)

	Rough	Complex	Interesting	Natural	Unusual	Beautiful	Valuable	Strong	Smooth	Simple	Boring	Artificial	Ordinary	Ugly	Worthless	Weak
Coir	100%	53%	67%	87%	67%	33%	20%	27%	0%	40%	13%	0%	20%	33%	60%	33%
Cordenka	47%	60%	60%	20%	27%	40%	60%	60%	40%	20%	20%	60%	33%	40%	7%	7%
Flax FE	60%	53%	87%	87%	20%	60%	53%	80%	27%	40%	13%	0%	40%	20%	7%	7%
Flax FT	100%	53%	40%	73%	20%	27%	20%	73%	0%	40%	40%	7%	53%	53%	33%	13%
Flax UT	60%	47%	40%	73%	13%	27%	27%	73%	20%	20%	53%	0%	47%	73%	53%	13%
Glass Fibre	40%	47%	33%	7%	27%	27%	40%	53%	47%	20%	47%	87%	47%	53%	53%	13%
Hemp	100%	53%	40%	100%	40%	0%	7%	13%	0%	33%	60%	0%	33%	87%	67%	33%
Jute	93%	40%	47%	87%	53%	20%	0%	7%	7%	33%	33%	7%	33%	80%	53%	60%
Sisal	33%	20%	7%	53%	20%	0%	0%	27%	67%	67%	73%	20%	33%	93%	80%	13%

Table S4. Favourable ratings for each material against various attributes (Visual-Tactile)

	Rough	**Complex**	**Interesting**	**Natural**	**Unusual**	**Beautiful**	**Valuable**	**Strong**	**Smooth**	**Simple**	**Boring**	**Artificial**	**Ordinary**	**Ugly**	**Worthless**	**Weak**
Coir	92%	62%	92%	100%	46%	85%	38%	38%	8%	15%	8%	0%	31%	15%	15%	31%
Cordenka	69%	23%	46%	23%	62%	23%	8%	54%	23%	23%	38%	69%	31%	77%	54%	23%
Flax FE	8%	92%	77%	62%	46%	69%	62%	77%	92%	8%	0%	15%	23%	31%	23%	15%
Flax FT	31%	38%	46%	54%	31%	54%	46%	77%	54%	38%	46%	31%	31%	31%	31%	8%
Flax UT	62%	31%	54%	62%	46%	23%	8%	8%	23%	23%	31%	8%	31%	69%	46%	62%
Glass Fibre	85%	46%	46%	8%	62%	31%	38%	69%	8%	23%	31%	85%	23%	62%	46%	23%
Hemp	38%	62%	69%	100%	38%	23%	38%	46%	46%	23%	23%	0%	38%	69%	23%	15%
Jute	31%	54%	77%	100%	31%	62%	31%	62%	69%	23%	23%	0%	31%	31%	23%	23%
Sisal	15%	31%	31%	46%	54%	23%	23%	23%	77%	62%	38%	31%	23%	69%	54%	31%

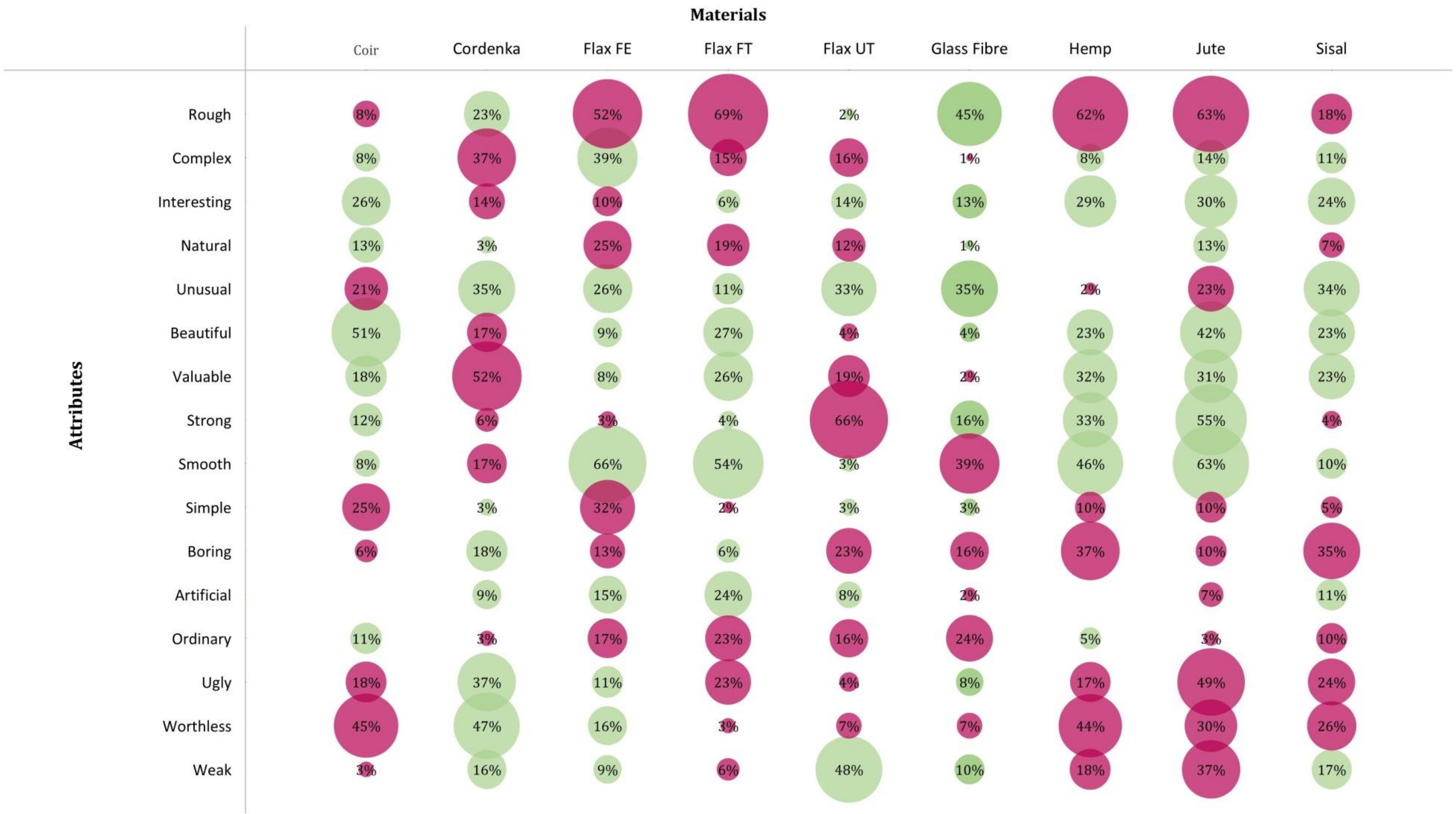

Figure S1. Change in favourable ratings when assessed in visual-tactile mode (%) (Green bubbles indicate an increase in favourable ratings and pink bubbles indicate a reduction in favourable ratings. Bubble sizes are proportional to changes in values)

Figure S2. Change in averages in each attribute scale when assessed in visual-tactile mode (Green bubbles indicate an increase in average rating (perception moving towards the right side of the attribute scale) and pink bubbles indicate a decrease in average rating (perception moving towards the left side of the attribute scale). Bubble sizes are proportional to changes in average rating)

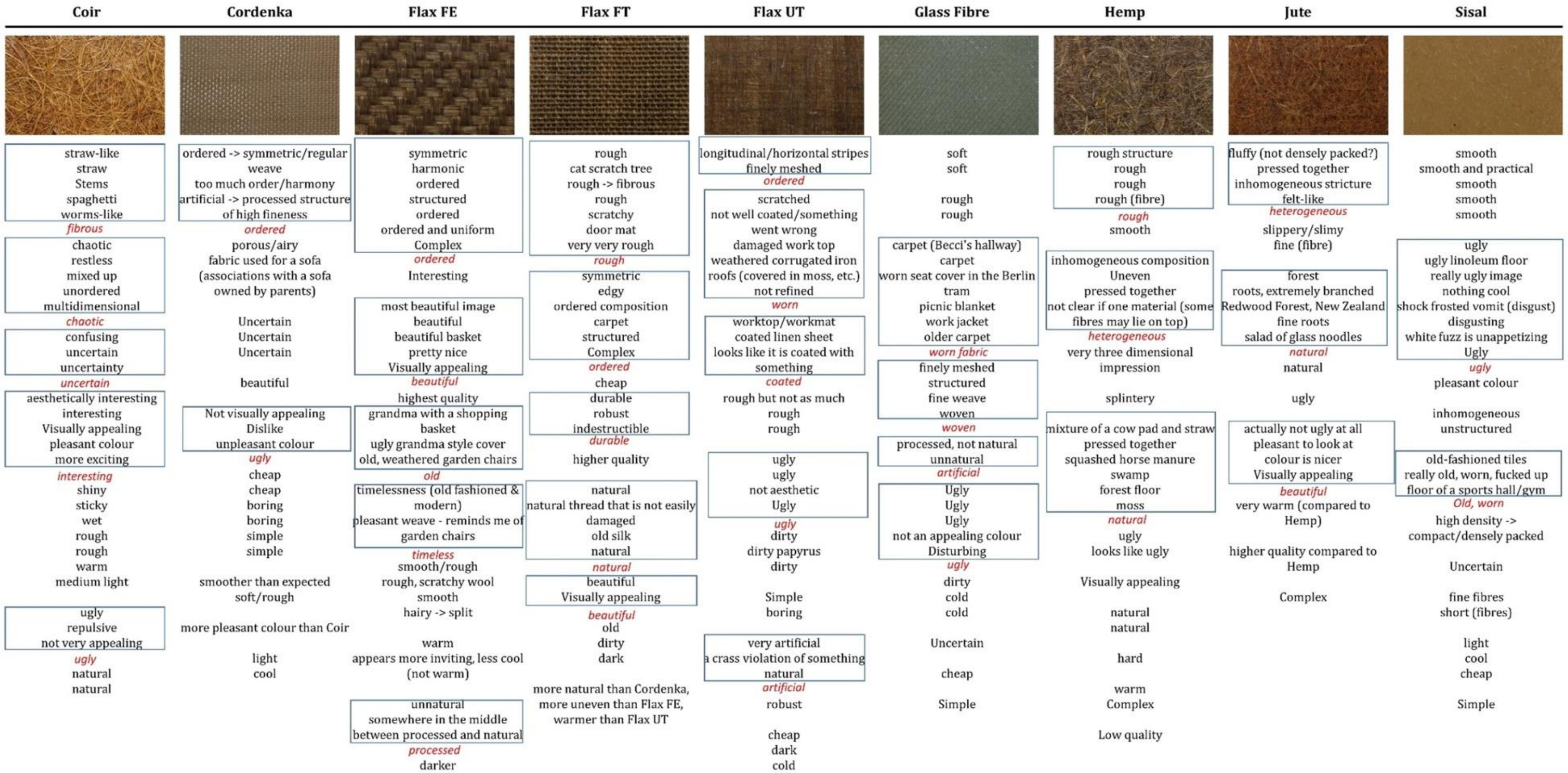

Figure S3. Raw list of adjectives used to describe various material samples. Synonymous descriptors have been combined in boxes with the generic adjective highlighted in red

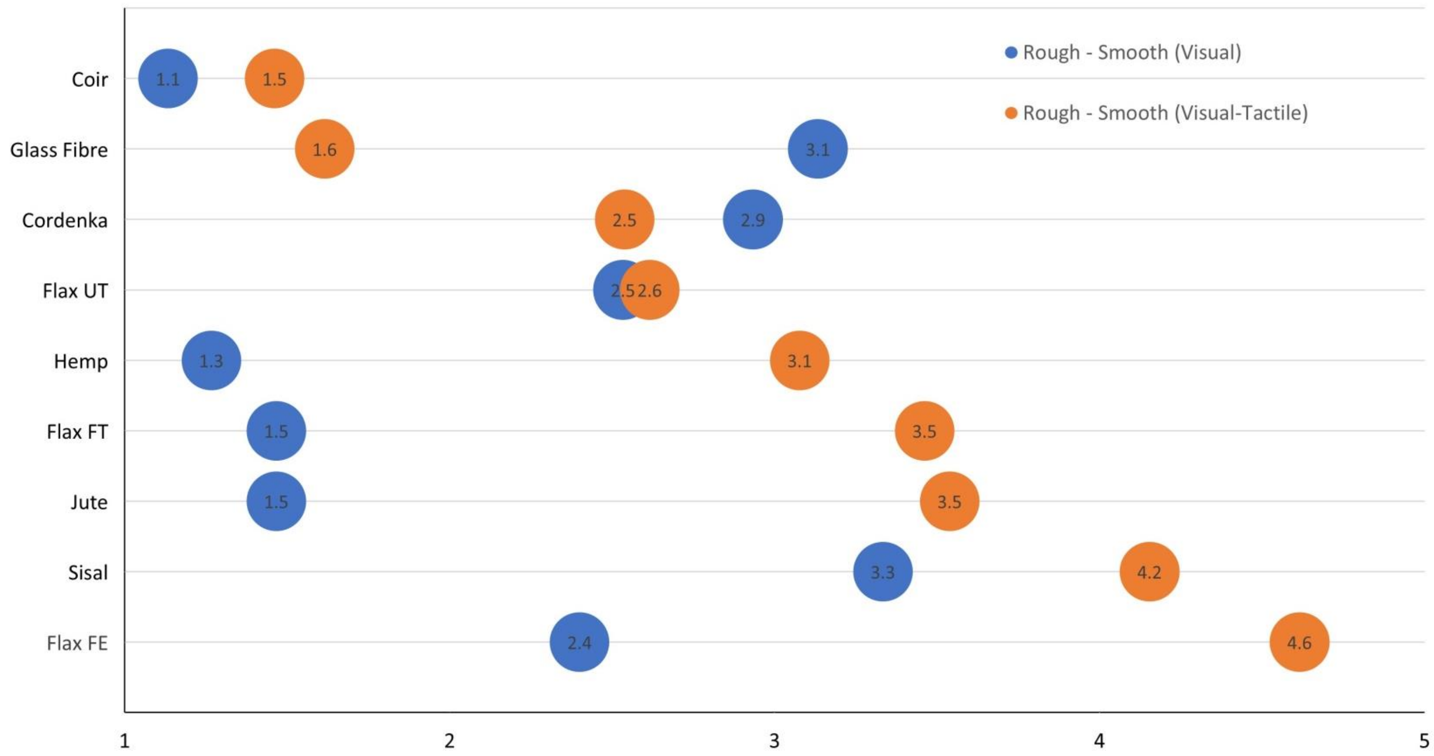

Figure S4. Comparison of rating average for each material on the Rough-Smooth scale

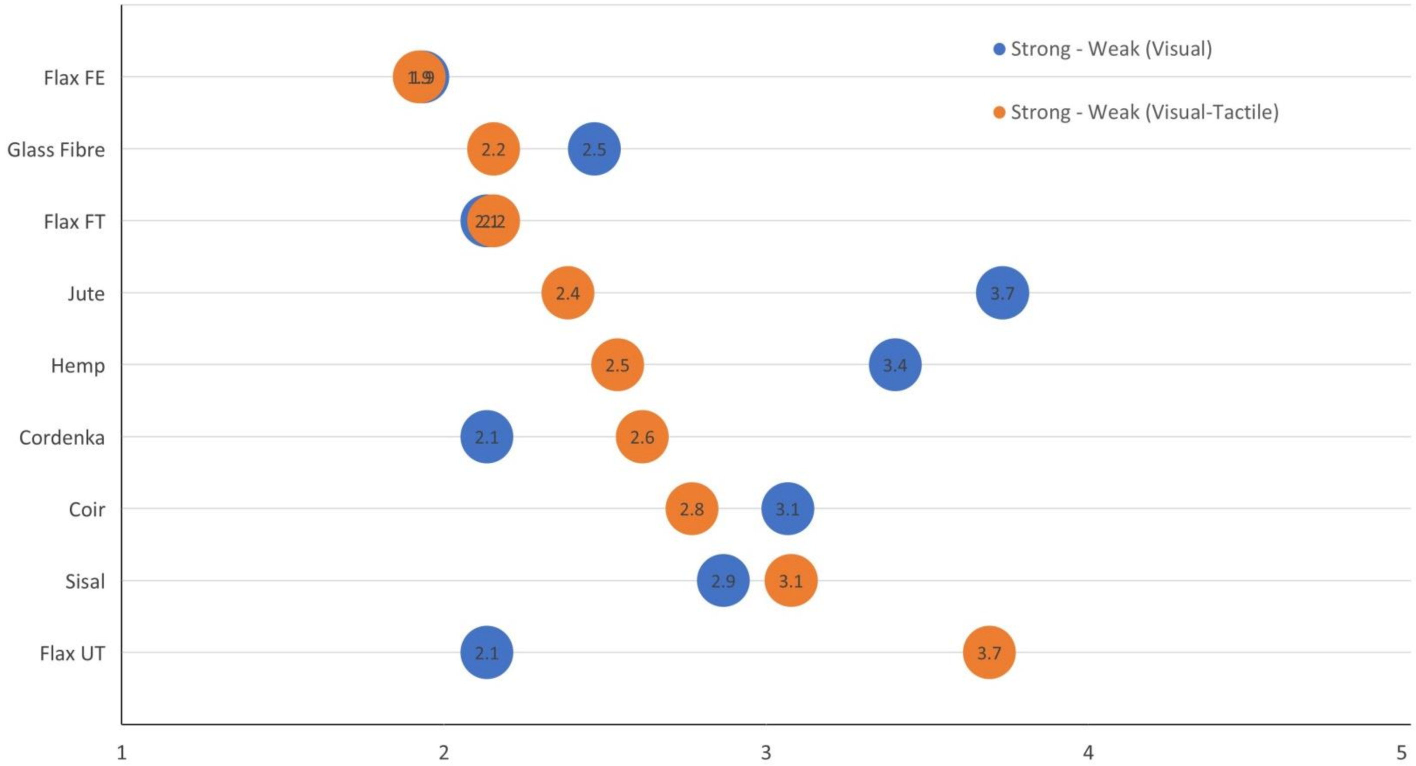

Figure S5. Comparison of average ratings on the Strong-Weak scale in two modes of assessments