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DESIGN WITH SUSTAINABLE MATERIALS: PREDICTING CONSUMER PERCEPTION OF BIOBASED COMPOSITES

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Abstract. The product designer's role in promoting sustainable materials is crucial, as designers make material selections for products on behalf of consumers. In this study, we examine this assertion of designers' ability to empathise with consumers and investigate if their perception of biobased composites aligns with that of consumers. A perception framework for biobased composites, proposed in prior research, is applied in this study to predict consumer perception of materials. The roles of various visual/tactile factors that affect crucial perceptual attributes (beauty, naturality, strength and value) are also examined. An evident perceptual incongruity between designers and consumers was observed, diminishing the claim of designers' ability to empathise with consumers in the remit of biobased composites. It is also noted that the proposed perception framework generates reliable predictions of consumer perception for biobased composites and can thus assist designers in material selection.

Keywords: *Biocomposites, material perception, product design, sustainable design.*

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1. Introduction

Biobased composites offer an attractive option in the search for a sustainable material substitute for fossil-based polymers (Correa *et al.*, 2019). These are created by combining two or more distinct biobased materials, forming a composite offering superior mechanical properties than its constituents. While this offers an attractive proposition, these materials are yet to significantly influence the product manufacturing industry, where most consumer products are still manufactured using fossil-based materials. The reasons for this inadequacy have been explored in detail, and beyond technical handicaps, poor consumer perception of these materials was identified as a significant cause (Manu *et al.*, 2022). Further explorations led to the development of a hypothesis- that the perception of materials could be linked with their visual and tactile characteristics and thus could be modified to create desired perceptual attributes. These investigations produced a perception framework based on key attributes that provide desirability and distinguishability (beauty, naturality, strength and value) to biobased composites (Thundathil *et al*., 2023a). This framework also established the impacts (both positive and negative) of various visual and tactile characteristics of conventional biobased composites on these core perceptual attributes. The visual/tactile characteristics of the biobased composites included fibreness, fibre patterns, fibre contrast, surface smoothness, and surface texture and reflection. The correlation of these sensory properties with material perception revealed the possibility of creating custom-perceived materials per the consumers' demands. Thus, this approach could predict how users perceive materials and allow designers to modify their perception by adjusting material characteristics. This prediction framework could also help develop sustainable materials that consumers better appreciate, and encourage more users and manufacturers to adopt sustainable material-based products.

In order to establish the validity of this perception framework, a study using a previously untested set of biobased composite samples is warranted. The perception framework was initially developed using a limited but representative set of standard biobased composites. This framework should be able to generate perception predictions about any new material, and aligning these predictions with consumer ratings will validate the framework's robustness. Prior studies as part of this research involved various biobased material samples, and the observations from these multiple studies were collated to form the biobased composite perception framework (Thundathil *et al*., 2023a). However, the insights from these studies may be limited due to factors such as (i) the presence of natural mono-material samples (e.g., wood, leather) as reference materials and (ii) the lack of qualitative-descriptive data on biobased composite perception. Our earlier studies on biobased composite perception (Thundathil *et al*., 2023a, 2023b) included natural mono-materials such as wood and leather to serve as reference materials, as the perception of these familiar materials is predictable. However, these natural mono-materials may have anchored the participants' perception of naturality by linking their visual and tactile characteristics with the perception of naturality (Tversky & Kahneman, 1974). While the impact of this anchoring effect is difficult to ascertain in a sample set, a sample set without any familiar natural materials would be less dependent on such biases.

The second limiting factor is the reliability of selecting various visual/tactile characteristics of biobased composites used in prior studies and linking them with perceptual attributes. In previous studies, the research team identified the main material characteristics of various material samples (such as the effect of fibres and surface finish), and inferences were drawn based on that material sample's performance against attribute scales. Though the research team consisted of domain experts and the sensory characteristics identified were objective, this still left room for bias. For example, the research team may have considered some aspects of the biobased composite to be more significant than others due to researcher bias, thus ignoring the less dominant material characteristics. A qualitative analysis, incorporating a descriptive exploration of material characteristics using experienced design professionals, would be appropriate to eliminate this; a qualitative study acknowledges the subjective nature of human behaviour and thus gives researchers a holistic view of the topic (Lord *et al*., 2009).

Another interesting factor is the assumption that designers can empathise with consumers regarding emotions felt while observing a material and thus be capable of predicting their material perception (Buchenau & Suri, 2000; Kouprie & Visser, 2009). Traditionally, a product designer selecting a material to manufacture a natural-themed product attempts to experience the naturality of various materials and empathise with a consumer. They then select the material with the strongest natural feeling suited for the product. This process makes the designer a proxy for the consumers and endows great power and responsibility with the designer to ensure that the consumers' preferences are accurately identified and represented. This aspect of a designer's role in the design process is often contentious, with many describing that it *"privileges the designer above the people she serves"*(Iskander, 2018). While defining a perception-based design methodology, it is crucial to understand how well the designers reflect the aspirations of consumers in terms of material perception. Comparing the predictions generated from the proposed framework with the material assessments of design experts would test this and uncover if there is an objective way to define material perception. Hence, the key objectives of this study were:

i. To compare the material perception between consumers and designers and to test whether the assessments are congruent.

ii. To test the perceptual relationships proposed earlier using a new set of biobased composite materials and to develop a prediction framework.

iii. Using qualitative data to enhance clarity on the relationships between visual and tactile characteristics of biobased composites and attribute perception.

2. Materials and Methods

The material sample set used in this study consisted of 16 samples, including experimental biobased composite samples and commercial samples sourced from various suppliers (Figure 1 and Table S1 in Supplementary Materials). Each sample was 45 mm x 45 mm in dimension, with varying thicknesses ranging from 1 mm to 7.2 mm. To eliminate the effect of thickness on attribute perception and to prevent participants from bending the samples, each sample was mounted inside 3D-printed cases with a thickness of 9 mm (Figure S1 in Supplementary Materials). This framing of samples limited the interactions of the study participants to seeing and feeling only the sample surface. The material samples were numbered using a random three-digit format to alleviate any bias due to sequential numbering.

Fifty-two students were recruited from the University of Canterbury for the quantitative part (Phase 1 - consumer group) of the study, and 12 design experts from Christchurch, New Zealand, were interviewed for the qualitative phase (Phase 2 - designer group) of the study. The designer group had a median professional experience of 20 years (minimum - 2 years, maximum - 35 years). Since no influence of age or gender was observed in a prior study as part of this research (Thundathil *et al.*, 2023b), convenience sampling was adopted for selecting participants. While cultural preferences may impact perception (Kastanakis & Voyer, 2014), the extent of this influence on material perception of biobased composites could not be explored as part of this research due to limitations in data collection.

In the first phase of the study, the 16 samples were presented to the participants, along with four attribute scales (*Natural-Artificial, Beautiful-Ugly, Valuable-Worthless* and *Strong-Weak*), identified as the key attributes from the biobased composite perception framework in Thundathil et al. (2023a). These attribute scales were presented in a linear Likert scale format (Figure 2), each offering five rating options. For example, for the *Natural-Artificial* scale, the options were 'Definitely Natural', 'Looks like Natural', 'Can't say', 'Looks like Artificial' and 'Definitely Artificial'. The participants were then asked to place the material samples on the rating scale, and a photograph of the arrangement was taken to enable timely data collection. This process was repeated for all the scales, and the resulting arrangement photographs were later converted into rating values (e.g., 1= Definitely Natural, 2= Looks like Natural, 3= Can't Say, 4= Looks like Artificial and 5= Definitely Artificial). This rating data was used to find each material's median attribute assessments and rank material ratings against each attribute scale. This ranked (ordinal) data was also used to establish correlations between attribute scales using Spearman's rank correlation method. The attribute ratings of consumers from Phase 1 of the study were collated to create a frequency distribution of ratings for each interval on the Likert scale; this way, the perceptual assessment of each material against various attributes could be easily visualised.

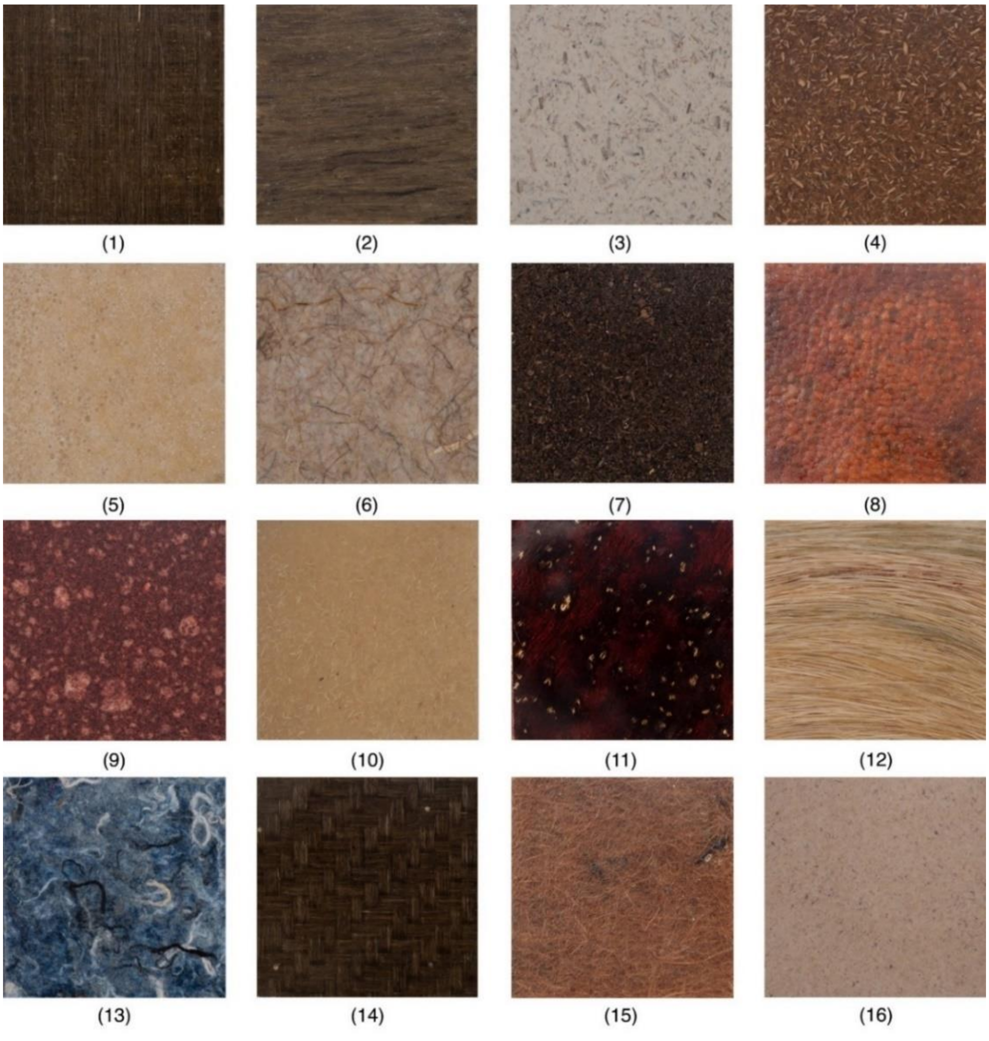

Figure 1. Samples used in the study: (1) Flax UT, (2) UD Flax tape, (3) N8010, (4) PB30XS- Brown, (5) ESO- Eggy, (6) N9010-Hemp, (7) LA-Earth, (8) Kelp, (9) SCALITE, (10), Sisal, (11) Barktex, (12) Harakeke, (13) N9010-Denim, (14) Flax FE, (15) Jute, (16) PB30XS

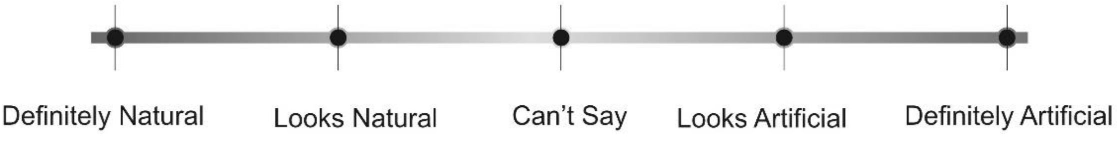

Figure 2. Example of an attribute scale used for attribute rating

In Phase 2, the same methodology used in Phase 1 was implemented to collect material perception data from design experts, followed by an open-ended interview. During the interview, the 12 design experts (designated D1 - D12 in the following sections) who constituted the designer group were asked to explain the logic behind their ratings for various materials on each attribute scale. Qualitative data collection was terminated at this point as saturation was achieved in the descriptive responses. The discussion focused on the material characteristics (visual and tactile), which prompted the respondent to form their assessment of the materials at hand. These interviews were recorded (audio only), later transcribed using Whisper AI (https://openai.com/research/whisper), and analysed using NVivo 1.7.1 (Lumivero, Denver, U.S.A.) to group similar responses and emotions. This was a qualitative study with deductive and inductive components (Bingham & Witkowsky, 2022); the deductive approach was used to validate the framework, and the inductive analysis was used to identify additional factors beyond the ones established in the perception framework. This study received ethics approval from the Human Research Ethics Committee of the University of Canterbury, New Zealand (Approval ref: HREC No. HREC 2023/07/LR-PS).

Before commencing the study, predictions of consumer perception were made for the 16 material samples used in the study, using the visual and tactile characteristics identified under the perception framework proposed by Thundathil et al. (2023a). The qualitative assessments from the prediction framework were converted to a quantitative scale to compare these predictions with the consumer perception data. This conversion was done by assigning a value of +1 for each visual/tactile characteristic of the material sample that improved perception (advantages) for each attribute scale. A score of -1 was also assigned for each negative characteristic-perception correlation (disadvantages). A value of ±1 was used since the characteristics were unweighted, and this offered a glimpse of the general perception trend. The unweighted sum of scores from all the visual/tactile attributes was considered as the net score of the material, and a positive score signalled a favourable perception, while a negative score indicated a poor perception for the relevant attribute scales. A sample worksheet is provided below to illustrate this methodology (Table 1). In this case, Harakeke (one of the material samples) had three positive characteristics and one negative characteristic, resulting in a net score of two. Once the materials were scored using this method, they were ranked by net scores, and then this ranking of materials was compared with the ranked perception data from the consumer survey to check their correlation. This ranked perception prediction model has been adopted to reflect the complex nature of measuring human perception and various external influences on it. Such complexity makes it difficult to generalise and quantify sensory perception (due to personal, environmental and cultural influences), and a ranked model would be able to contain variances emanating from such influences.

Table 1. Example for the prediction of perception and conversion to ranks

Material		Properties	Naturality	
			Advantages	Disadvantages
Harakeke	*Visual property*	Long, organically oriented fibres	High fibreness leads to high naturality (+1)	
		Contrasting fibre arrangement	Improved fibreness leading to naturality (+1)	
	Tactile Property	Fine texture, wood-like (oriented roughness)	Oriented roughness improves naturality (+1)	Smoothness leads to artificiality (-1)
		Net Score: +2	+3	-1

3. Results and Discussion

3.1. Can designers predict consumer perception?

The first objective of this study was to determine if the material perception assessments of the designers resonated with those of consumers, and hence, whether they can effectively empathise with their consumers. This scrutiny is crucial since product designers select materials for the products being designed based on their ability to empathise with the consumers (Sparke & Fisher, 2016; Zingoni, 2019). However, in this study, Pearson's correlation test of overall material rankings by consumers and designers revealed no statistically significant correlation between these groups. Moreover, it was observed (through assessment medians) that designers' perceptions differed from those of consumers in the case of certain materials (Table 2).

Table 2. Materials where the opinions between both groups vastly differed (polar assessments of perception)

Material	Consumers	Designers
Barktex	Looks like Beautiful Looks like Valuable	Looks like Ugly Looks like Worthless
Flax FE	Looks like Beautiful Looks like Valuable	Looks like Ugly Looks like Worthless
Flax UT	Looks like Natural	Looks like Artificial
N9010-Denim	Looks like Artificial	Looks like Natural
Harakeke	Looks like Worthless	Looks like Valuable

While investigating the various reasons for this perceptual dissonance in designers, the following two possibilities were observed in the analysis of interview transcripts:

i. Familiarity with a multitude of materials;
ii. Domain bias.

Most of the designers interviewed for this study had extensive exposure to various materials, leading them to make confident (and at times inaccurate) assessments about the novel material classes they encountered. This reference to familiar materials may have created a bias while assessing biobased composite samples, and often made them miss the finer sensory characteristics of the assessed sample. It is reasonable to assume that the respondents in the consumer group had relatively less exposure to novel materials than designers because deep knowledge of material selection is an essential facet of professional designers' trade (Haug, 2019). Hence, they may have approached the assessments heavily dependent on sensory stimuli and less on the cognitive processing of material knowledge. Designers often immediately classified the biobased composite into a familiar material group (countertop material, chipboard, stone, leather), which then induced the perceptual values of this familiar group on the material assessments. E.g., a designer [D6] made the following comment when discussing their logic in assessing naturality in materials:

> *"I guess this one might come from a bit of experience…. more of things we've dealt or been working with some natural materials that look very similar to that. And so, I might be swayed more by that than whether it actually is (natural)…"*

The perceptual familiarity of designers with materials often did not align with the actual market prevalence of the material. An example of familiarity leading to a more negative perception was the case of Flax FE, which resembled a woven carbon-fibre composite. The herringbone pattern and glossy surface of the material were considered generic, ordinary and boring by the designers (and hence ugly and worthless), irrespective of very few mass-produced consumer products having that finish. The consumer group, however, found this material to be beautiful and valuable (Table 2). Another significant observation during Phase 2 of the study was that designers often assessed materials in the limited context of their practising design domains. So, a furniture designer would imagine the assessed material being used in a piece of furniture and imagine the perception in that context; a communication equipment designer would consider the material in that context. Such contextualising of materials in different settings often imbues certain qualities associated with the product segment and leads to incongruity among designers. Designers frequently cited the lack of context as an issue for assessing perception, presumably because material selection comes after the development of a tangible form in the traditional design process (Taylor, 2014). This ad-hoc assignment of context was evident in a designer's [D8] comments on assessing the beauty of a material sample:

> *"… there's no context here, but it's sort of like, I kind of have like a made-up context in my head of… (things) you could make…. for me, it's doing lots of kitchens and lots of interesting kitchens at the moment. And if I could use this as a material in that context… this is something we're not using… we want to look at interesting things…"*

As in the case of material familiarity, an average consumer may be less influenced by these contextual constraints and could assess the materials purely for their physical qualities without a product context.

3.2. Factors Affecting Core Attributes

3.2.1. Beauty

Among the material samples, only N9010-Denim was rated as 'Definitely Beautiful' by the consumer group. While 8 out of 16 samples were deemed beautiful to some extent, three materials (LA Earth, PB30XS Brown & Sisal) were judged somewhat ugly by the consumers; the rest were deemed to have an uncertain perception (Can't Say). Figure 3 shows the rating trends for materials rated as 'definitely/looks like beautiful' by the consumer group. Most of these show strong and confident opinions, evidenced by high beautiful ratings (Definitely/Looks like), with low uncertainty (Can't say ratings).

An interesting aspect of the top-rated material for beauty, N9010-Denim, was that it exhibited similar median assessments between the consumer and designer groups (consumers - *Definitely Beautiful*, designers - *Looks like Beautiful*) (Figure 5). This congruence was despite the strong assertions by multiple designers during the interview that beauty is subjective and cannot be defined by a specific standard. However, the similarity in assessments of N9010-Denim among the two groups suggests that there may be some general underlying factors that influence people's perception of material beauty, independent of their level of design expertise, as hypothesised in the perception framework (Thundathil *et al*., 2023a).

One of the factors contributing to this may be visual simplicity (or the lack thereof) in material surfaces. In the long-established modernist approach, visual simplicity was attributed to beauty, but too simple or plain visuals were considered boring and hence undesirable. An explanation for this phenomenon, rooted in the study of evolutionary aesthetics, is the theory of Efficient Processing (Renoult, 2016). In the case of moderately complex visuals (as in the case of N9010-Denim), the designers felt that beauty depends upon the scale and resolution of fibre patterns on the material surface. These aspects of the fibre pattern enabled the viewer to discover new visual patterns with increasing size of the material or decreasing distance from the material. For example, the pattern in N9010-Denim gives certain visual stimuli for an observer at a distance, but as they come closer and closer to the material surface, finer details are revealed, thereby delivering novel visual stimuli to the viewer. This aspect creates interestingness and novelty in the visual experience, contributing to beauty (pleasurable aesthetic experience) (Hekkert *et al*., 2003; Menninghaus *et al*., 2019).

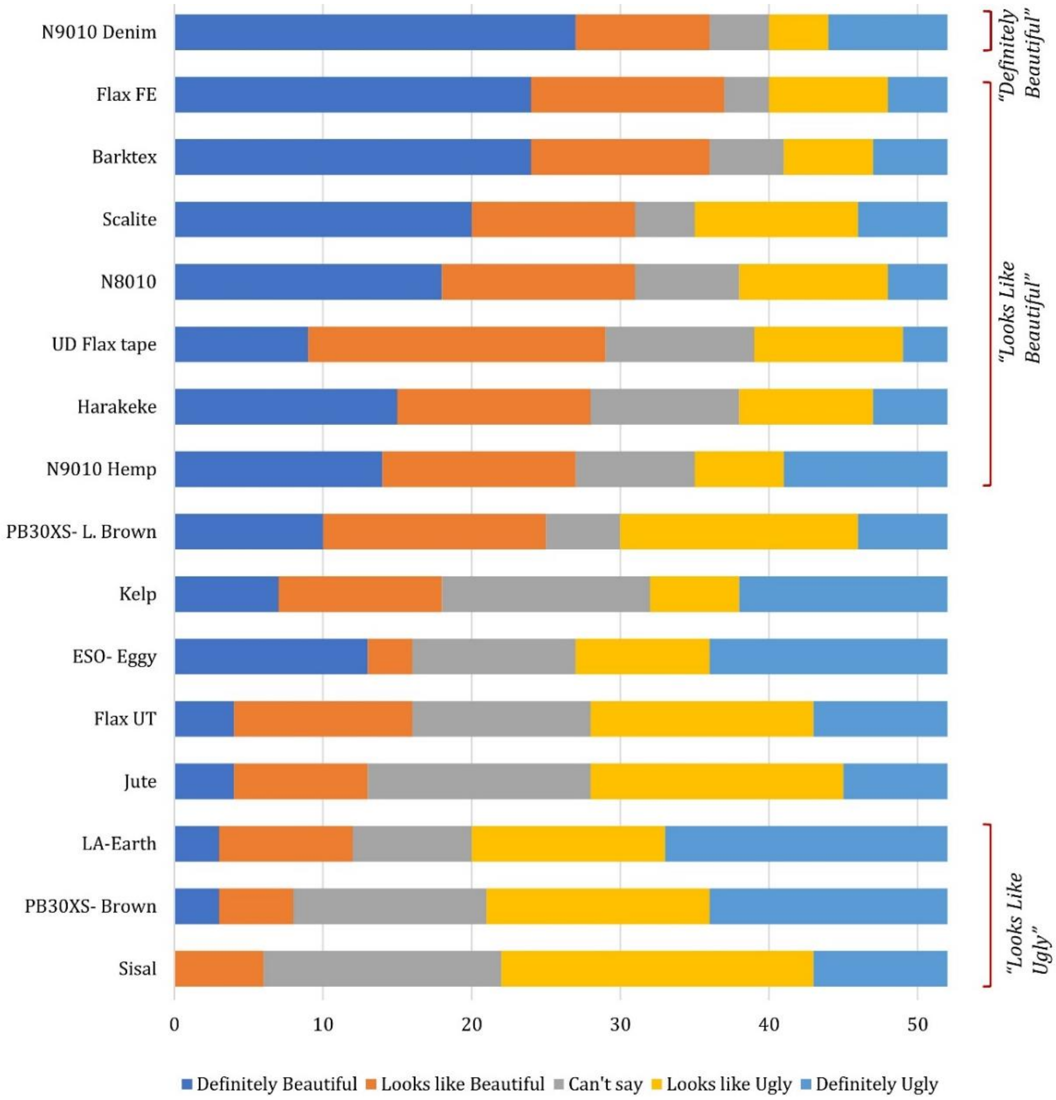

Figure 3. Rating frequency distribution of various materials on the Beautiful-Ugly scale

Another factor is the colour, contrast and composition of elements (e.g., fibres) within the polymer matrix. They revealed the roles of visual harmony and balance in forming the perception of beauty, which has been previously suggested by Smith (1980). The contrast of fibres with the resin matrix is also essential; very low contrast may result in a visually plain appearance, while very high contrast may result in visual confusion, both unfavourable to beauty. Dark colours were not generally well received by designers who opined that light colours enhanced the perception of beauty, but this emotion did not resonate with the ratings of the consumer group. Another contradiction arose in the case of Barktex and Flax FE - materials ranked second and third in beauty by the consumer group. The designer group had polar opinions about these materials (Barktex: Looks Like Beautiful (consumers)/ Looks Like Ugly (designers), Flax FE: Looks Like Beautiful (consumers)/ Looks Like Ugly (designers)), underscoring the perceptual dissonance between the designers and consumers. A reason for designers having this poor opinion about such materials may be a lack of novelty or familiarity with such materials, as discussed. The novelty of the material was an essential aspect for designers in assessing value *("...I would pay extra to be able to use that because there's nothing else like it that looks like it..."* [D11]) or even beauty (often correlating with each other). For example, Scalite, which had a novel visual appearance, had high ratings for beauty and value by both survey groups.

Familiarity was linked with ugliness, but this relation was strictly limited to materials resembling artificial materials. In the case of natural-perceived materials (biobased composites resembling natural materials - e.g., Harakeke - bamboo, Jute - leather, N9010-Hemp/N8010 - Granite/marble), naturality also resulted in the evocation of beauty, which may be attributed to biophilia (Wilson, 1984) and the social esteem associated with high-value natural materials (Ludden *et al*., 2012). In the case of Barktex and Flax FE, they were considered akin to engineered biobased panels (plywood/laminates), commonly available with glossy topcoats. This familiarity with the material finish and the low value of reference analogues may have prompted the designers to go beyond purely sensory perception and perceive low beauty in these materials. This impact of references to undesirable or low-value products causing ugliness was most evident in the case of PB30XS Brown and Sisal (Figure 4), which were compared to chipboard-like products. This argument is corroborated by the low-value assessment for these materials as well.

The visual depth of material surfaces was often highlighted as a desirable feature; this visual depth, formed as a consequence of the translucent resin matrix, also created interestingness and thus reinforced the perception of beauty. Sensory conflicts or contradictions where there was an optimum degree of incongruity (Flax FE/UD Flax tape/Harakeke: visually rough, tactually smooth) created surprise in consumers, followed by positive sensations and thus desirability (Ludden *et al*., 2012).

A consistent and smooth surface finish was also linked with beauty; while the designer group rated a smooth, satin finish as the best, the consumer group disliked rough surfaces (e.g., LA-Earth), pointing to some consensus in correlations about roughness and ugliness. However, this attribute may not be a direct effect of surface flatness, but rather due to low sliding friction between the human finger and material surfaces. Carbon and Jakesch (2013), in their functional model for haptic aesthetics, describe these attributes as 'stickiness' or 'braking' qualities of the material surface and consider them in the first level of material interaction. Highly glossy surfaces also create such 'stickiness/braking', which results in an undesirable assessment and if the fine roughness (or satin finish) was achieved through a texture, that adds a layer of tactile interestingness to the material, thereby improving desirability. Hence, it may be assumed that the perception of beauty in biobased composites is dependent primarily on visual characteristics (visual depth, filler patterns, simplicity, colour, contrast and harmony) but is also influenced by surface characteristics to a limited extent, as hypothesised in Thundathil et al. (2024).

3.2.2. Naturality

The consumer group rated Harakeke and LA-Earth as 'Definitely Natural', and the ratings by the designer group reflect similar assessments (Harakeke - *Definitely Natural*, LA-Earth - *Looks like Natural*). Figure 4 illustrates the perceptual assessment trends of the materials rated highly for naturality. Harakeke and LA-Earth show a dominant rating trend for naturality, while all other materials exhibit a moderately linear relationship. In all the top natural-rated materials (barring ESO-Eggy), fibreness was considered the most significant indicator of naturality. A designer (D1) commented - "*…where you have more fibre, you see somehow the material more. And seeing that material also gives you the idea that it's a natural material compared to an artificial one*".

Visual similarity with familiar natural mono-materials (wood, leather, stone) contributed to the feeling of naturality as well, in the case of some biobased composites (Harakeke -Wood, Jute -Leather, N9010-Hemp & ESO-Eggy - Stone). A respondent in the designer group felt that the jute biobased composite (Jute) was very similar to leather- "*…that does look like a beautiful leather. And I could even show you some of the leather samples. They wouldn't be too far away from that…*" [D7].

It was also observed that being natural alone cannot ensure the perception of naturality unless the material is familiar as a natural material to the consumer. This effect was evident in the case of Kelp, where, though the material was biological, the unfamiliarity with its surface properties made consumers rate it as 'Can't Say'. However, the designers reasoned the material to be unfamiliar but organic (though incorrectly as some variety of leather), resulting in a rating of 'Looks like Natural'. A similar difference in opinion was observed for N9010-Denim as well, highlighting the impact of material familiarity in forming perception.

Smooth or glossy finish on material surfaces depreciated naturality ratings for both groups; such sensory consistency also indicated some human/process intervention and thus more artificiality - "*…the smoother it is, the more artificial it gets…*" [D2] and inconsistencies and inclusions were accepted as natural - "*…the inconsistency in it is the interesting thing… it seems very natural…*" [D8]. High gloss also resulted in the feeling of a laminated or coated surface, thereby exacerbating the artificiality of the material (e.g., Flax FE). Visual patterns (like weaves), even on natural fibres, signalled artificiality, whereas organic patterns improved naturality - *"…perceived randomness in the patterning… is going give you a sense of if it's artificial or natural…"* [D12].

Alignment of fibres was also noted for its impact on naturality for both designers and consumers; in the case of random, chaotic fibres, colour and low fibreness (as in N9010-Denim, N8010) contributed to artificiality, while a harmonious and rhythmic fibre arrangement of packed contrasting fibres (as seen in wood grains) elevated naturality (as in Harakeke, LA-Earth). While this study did not explore the impact of colour on material perception, N9010-Denim provided a small glimpse of this effect. N9010-Denim had a blue hue, which is uncommon in familiar natural substrates. Predictably, the consumer group considered this material artificial due to the lack of familiarity with biobased composite manufacturing (*Looks Like Artificial*), but the designers rated these materials as *Looks Like Natural*. This conflict could be attributed to the designers' knowledge of materials and processes, and most of them strongly associated N9010-Denim with natural fibres and justified the unusual colour by the possibility of dyeing ("*...for me it looks like a wool... it's been pressed (and) there's been a dye put in it...*") [D7].

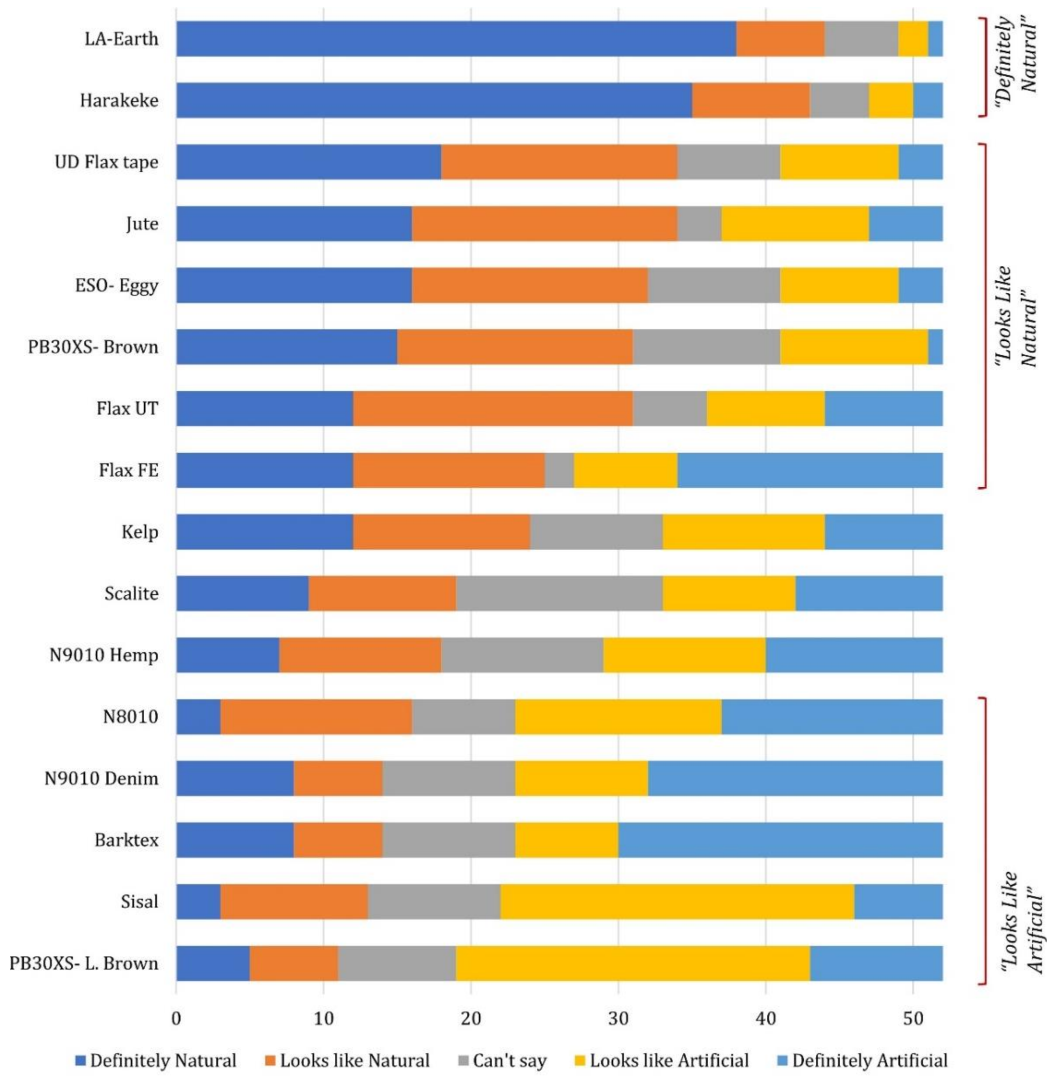

Figure 4. Rating frequency distribution of various materials on the Natural-Artificial scale

3.2.3. Strength

N8010 was rated as the strongest material (*Looks Like Strong*) by the consumer group (Figure 5), which was aligned with the rating of the designer group (*Definitely Strong*). The weakest-rated material by the consumer group, LA-Earth (*Looks Like Weak*), also received a similar rating by designers (*Definitely Weak*). In the case of N8010, it reminded many designers overwhelmingly of materials used for kitchen benchtops (marble, Formica®, Corian®) and this association created a perception of strength. N8010 had a hard and non-porous surface, which made respondents describe it as "stone-like / granite-like", evoking a perception of strength. Another interesting aspect was the perception of the 'coldness' of the material surface, further eliciting the feeling - "*...So, it -the marble one- jumps out because it's cold and therefore it's hard and it's strong…"* [D1].

In the case of Barktex, which was also rated strong by both groups, similar factors were in play - high gloss, cold feeling and artificiality (*"...I think the less natural, the stronger in some cases…"* [D2] and *"…it doesn't feel porous and is high-gloss, colder and therefore feels like this would be stronger…"* [D1]).

Flax FE was considered *Strong* due to its woven structure, which respondents recalled as "*carbon fibre-like"* [D10, D12] and reported that *"…this reminds me of carbon fibre, so I probably would put that into the very strong..."* [D3]. This impact of referring to familiar materials was significant in the designer group, and the characteristics of the reference material might have affected the attribute perception of the material sample. While Flax FE was associated chiefly with carbon fibre composites, inducing a perception of strength, it was also compared with natural fibres (e.g., flax fibres) by a few. Interestingly, the material was deemed weak when associated with natural fibres.

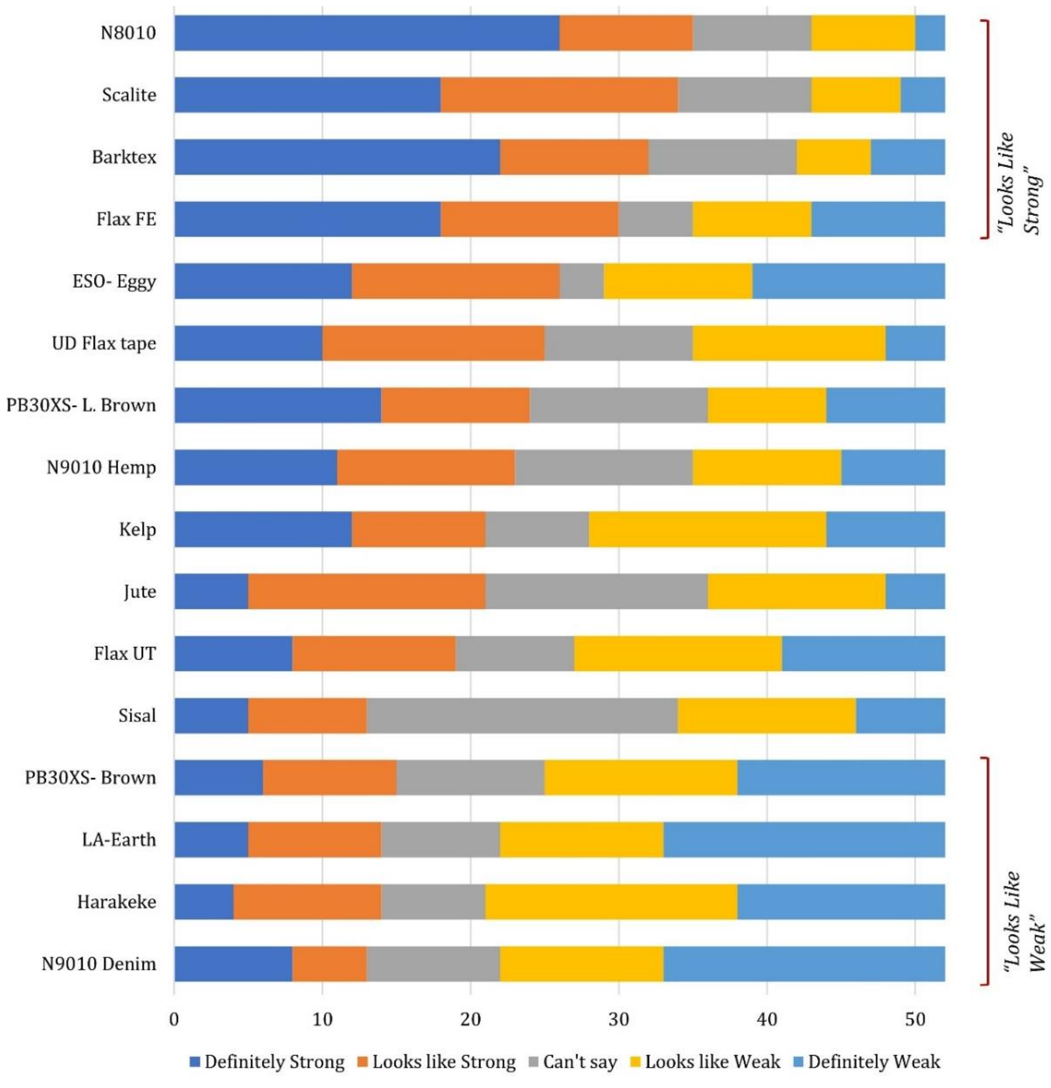

Figure 5. Rating frequency distribution of various materials on the Strong-Weak scale

In the case of weak materials, LA-Earth was considered the weakest by both groups. The reasons for this are evident from the designer group, where the participants used terms such as "*porous*", "*unstable*", *“inconsistent”* and *“cork-like”* to describe this material. Many also felt that the lack of visible long fibres reduced the chance of the material being held together. While references to strong materials, such as stone, marble, and carbon fibre laminates, imparted a perception of strength, the opposite was also true. Samples similar to softer materials like leather (Jute) or felt (N9010-Denim) reduced the perception of strength.

Natural-rated materials were more likely to be rated weak as well by consumers; a significant negative correlation ($r=-0.51$, $p\text{-value}<0.05$) was observed between ratings for *Artificial* and *Weak*. The reason for this could be the fact that along with artificiality, the expectations for higher functional properties rose, fixing the default expectation to be not weak - *“... there's something about the artificiality of it that makes it feel like if someone had put that much effort into it, that they've done so to make it strong or for a purpose…”* [D6]. Inconsistency in material characteristics also created a perception of weakness, which was higher in natural-perceived materials. In short, materials with smooth, hard, consistent and cold-to-touch surfaces, similar to other strong materials like marble and carbon fibre composites, were perceived as strong. Creating new biobased composites with such material characteristics would improve their strength perception.

3.2.4. Value

In the assessment for value, Barktex was rated the highest by consumers (*Looks Like Valuable*), which conflicted with the perception of designers (*Looks Like Worthless*) (Figure 6). This conflict was also observed for Flax FE; however, both groups had converging perceptions about Scalite and N8010 (*Looks Like Valuable*). The consumer group considered LA-Earth, Sisal and PB30XS-Brown the most worthless materials, but these assessments often conflicted with designers' perceptions.

The ratings for value by the consumer group correlated significantly with the ratings for beauty and strength, and this relationship is evident in the top strong/weak materials. The key attributes that could have aided Barktex in becoming the most valuable material could be the novelty of the material and visual interestingness. Barktex was unfamiliar to the user group, with its organic visual character and glossy surface finish, offering an optimal value-arousal as suggested by Berylne (1970). In the case of Flax FE, it had consistent, smooth surfaces and patterns, which signify quality and strength, promoting the perception of value.

As in the case of strength and naturality, material associations also influenced the perception of value in the case of designers. Material associations with materials that are generally considered valuable (carbon fibre-reinforced composites, marble, leather) or those that are considered cheap (chipboard, cork, felt) influenced the designers to assign values to the biobased composites in this study, “*...I think it's symbology. It reminds me of things I've seen that have been made from materials that look similar…”* [D4].

The hypothesis that the perception of value is derived from the combination of *aesthetic value* (beauty, novelty, interestingness) and *functional value* (strength, durability, functionality) (Thundathil *et al*., 2023a) is evident in this study as well. Five designers opined that their perception of value was purely on interestingness or the novelty of the material, commenting that “*...I just don't like the look of it. It's just ugly and I think if I perceive something as ugly, I perceive something as worthless…”* [D2] or

"…in my brain, they're really interesting and highly valuable. There's nothing like them. And I look at that and go, wow, that's cool. I would pay extra to be able to use that because there's nothing else like it that looks like it… it's the fact that they don't have any familiarity which puts them at the top…" [D11]

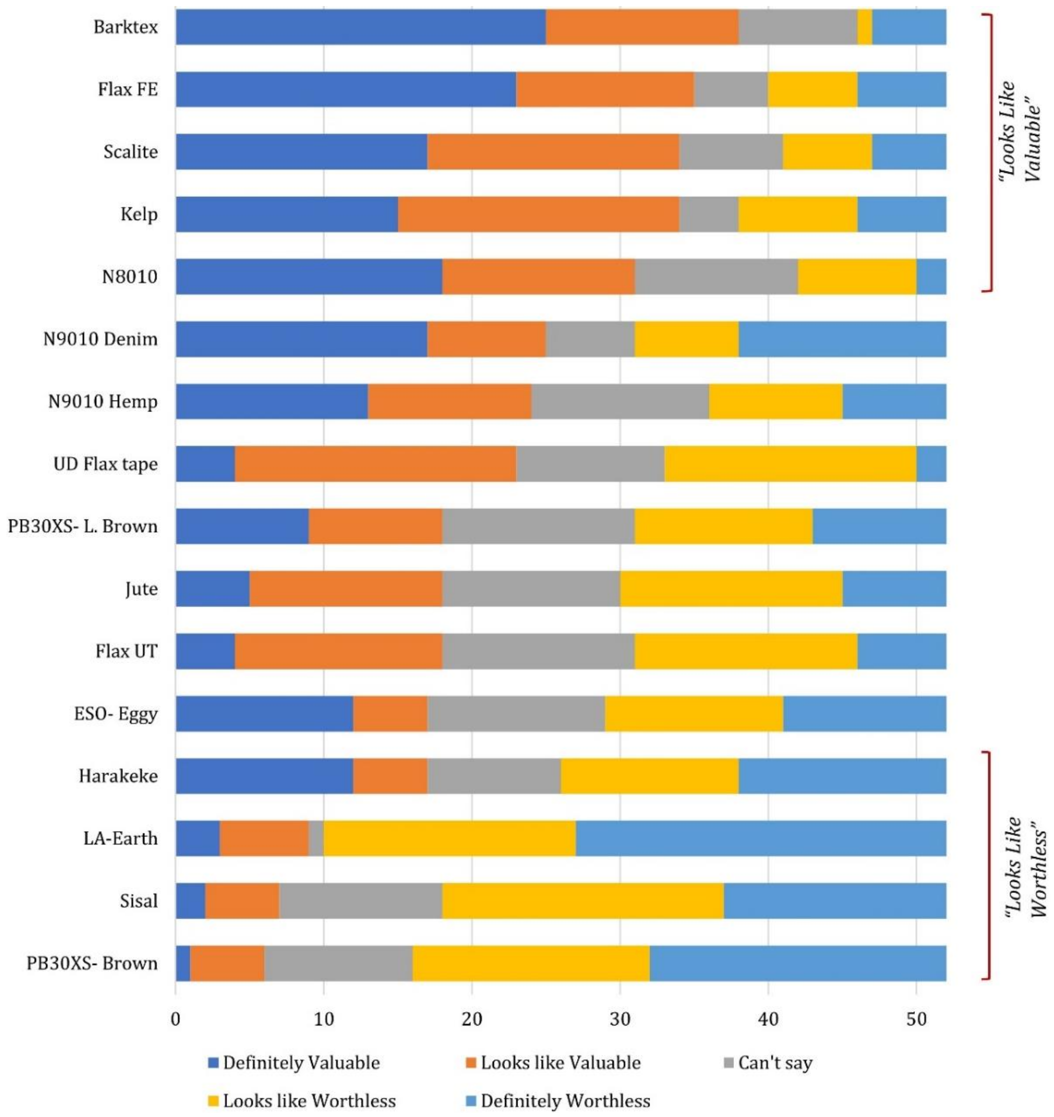

Figure 6. Rating frequency distribution of various materials on the Valuable-Worthless scale

In this case, the visual novelty need not be solely achieved through surface finish but could also be achieved through a novel manufacturing process. Another aspect of perceiving value was the implied quality of the material, often sensed through surface smoothness or sensory consistency. So, a smoother and visually consistent material was more likely to be considered more valuable than a rough, visually random material. But in the case of uneven surface qualities, they evoked materials made through highly labour-intensive processes (e.g., handmade paper) that add value as well –

"... The reason for this is, to me, they look almost handmade... And so, you have that aspect of... somebody's time has gone into this. And so this is what I would imagine, like an expensive notebook to be bound with. And so I think, in my mind,

this has a value perceived, not in the use of the product, but in, I guess, the time or the materials that have gone into making it. It's that kind of homemade, handmade kind of thing...” [D10].

Hence, the perception of value could be considered more influenced by material associations than purely by visual-tactile stimuli.

3.3. Desirable, Natural-Perceived Materials

The biobased composite perception framework (Thundathil *et al*., 2023a) adopts the premise that for a biobased composite to be successful in the consumer market, it should have good ratings for the core attributes: desirability (beauty, strength and value) and distinguishability (naturality). If the ranks for all these positive attributes are combined to reveal desirable natural materials, the top-ranked materials are given in Figure 7.

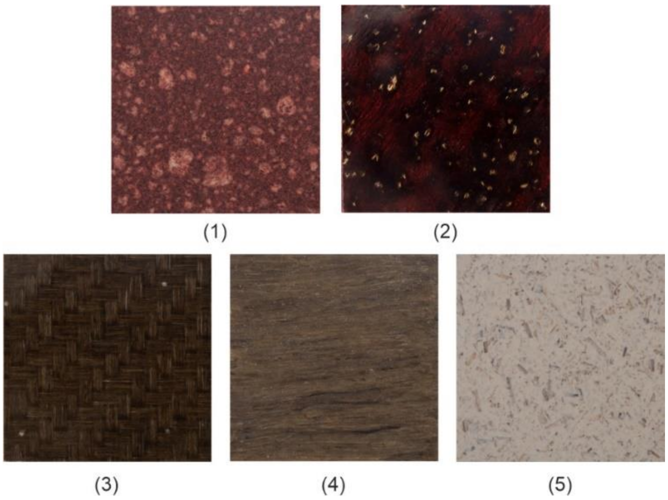

Figure 7. Top combined-ranked materials in the study: (1) Scalite, (2) Barktex, (3) Flax FE, (4) UD Fax tape and (5) N8010

So, for a product aiming to highlight the attributes defined in this study (beautiful, strong, valuable and natural), the materials listed above would be the best choices in terms of materials in this group to evoke the desired emotions. Likewise, if the intention is to select a material (in this group) that best reflects beauty, strength and value, then the top choices would be Scalite (1), Barktex (2) and N8010 (5). The top-ranked materials in each attribute or attribute-attribute combination are illustrated in Figure 8.

11 out of the 16 samples used in this study had uncertain perception in at least one attribute scale, with six materials having mostly uncertain perception (3 out of 4 scales) (Table 3). This uncertainty could be because these materials had a very unfamiliar sensory profile, creating confusion, or the respondents did not feel confident placing them on a particular attribute scale. This result also points to the vital fact that the perception of all materials cannot be classified into specific attributes, and intentional design is required to create materials with desirable perceptual qualities.

Figure 8. Top-ranked materials in each attribute and attribute-attribute combinations (consumer group)

Table 3. Materials with an uncertain perception in the consumer group (median rating: Can't Say; not included in graphs)

Material	Beautiful - Ugly	Strong-Weak	Valuable-Worthless	Natural - Artificial
Flax UT	⨂	⨂	⨂	
ESO Eggy	⨂	⨂	⨂	
Kelp	⨂	⨂		⨂
Jute	⨂	⨂	⨂	
PB30XS- L. Brown	⨂	⨂	⨂	
N9010-Hemp		⨂	⨂	⨂
UD Flax Tape		⨂	⨂	
Sisal		⨂		
N9010-Denim			⨂	
Scalite				⨂
Flax FE				⨂

3.4. Testing the Perception Framework

To test the biobased composite perception framework proposed by Thundathil et al. (2023a), the predicted rankings (as per the framework) were compared with consumer rankings of materials under various attributes. The correlation of ranks (using Pearson's correlation method) derived through the perception predictions with the consumer survey ranks was found to correlate significantly, pointing to the validity of the proposed biobased composite perception mechanism. While naturality and beauty showed high significance at α=0.01, strength and value were significant at α=0.05.

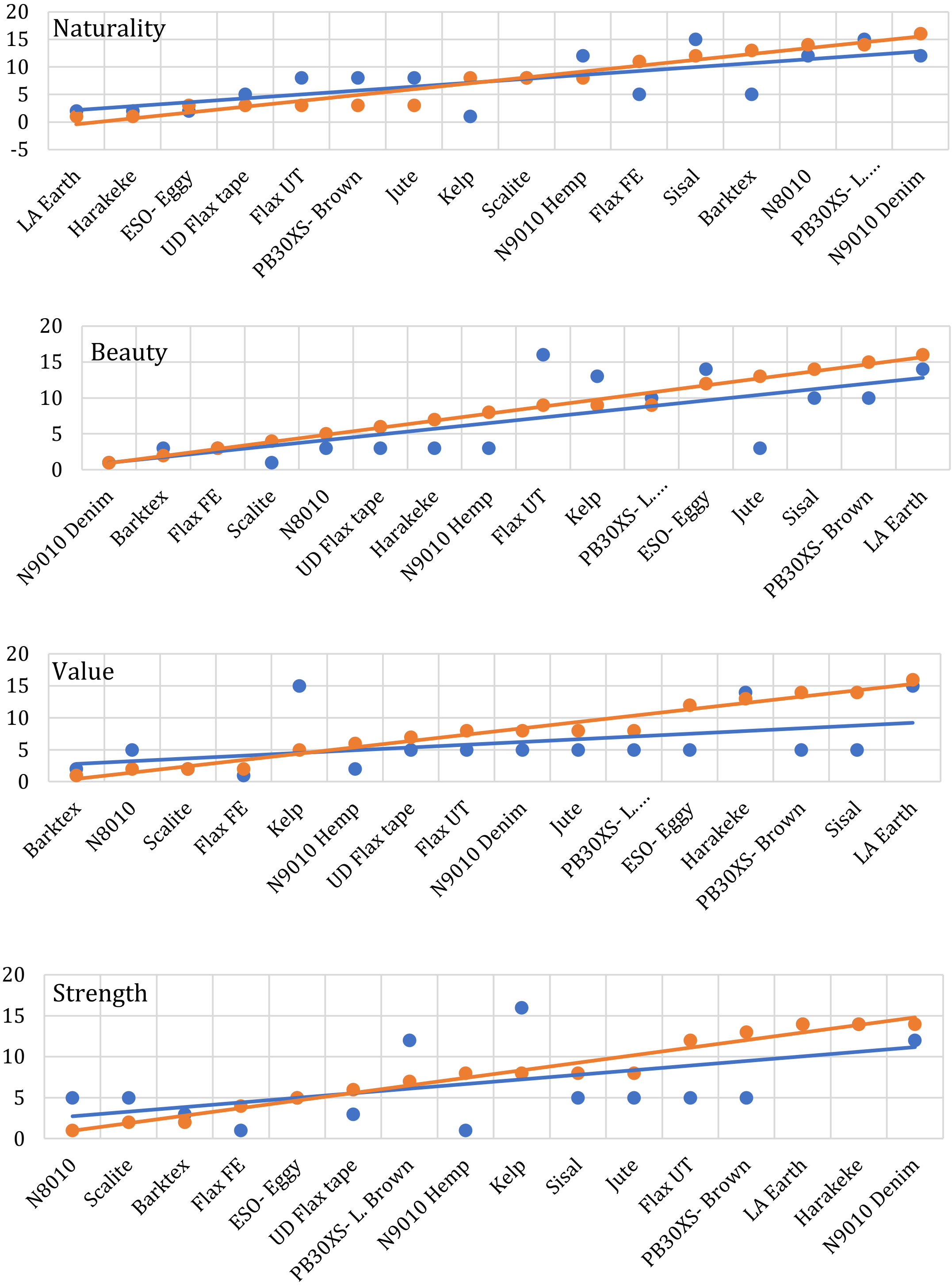

Figure 9. A comparison of ranking predictions of biobased composite samples based on the perception framework (in blue) and the ranking from the consumer survey (in orange) shows a high correlation. The Y-axis indicates the ranks assigned to each material on the X-axis through the consumer survey and prediction algorithm.

The comparison of ranks and their trendlines (Figure 9) reveals the correlations in trends and outliers that defied the predictions. The biobased composite perception framework proposed earlier (Thundathil *et al.*, 2023a) hypothesised a positive correlation between perceptions of beauty, naturality and value. Also, that value was composed of *aesthetic value* (influenced by beauty and naturality) and *functional value* (influenced by strength). Aesthetic value positively correlated with naturality and beauty, while functional value negatively correlated with those. The current study validated most of these correlations, excluding the relationship between naturality and beauty (Table 4).

Table 4. Correlation of various attribute ratings in the consumer survey

	Beautiful	Ugly	Natural	Artificial	Strong	Weak	Valuable
Ugly	-0.948**						
Natural	-0.281	0.283					
Artificial	0.349	-0.362	-0.958**				
Strong	0.546*	-0.425	-0.162	0.207			
Weak	-0.362	0.313	0.440	-0.510*	-0.819**		
Valuable	0.838**	-0.800**	-0.366	0.442	0.642**	-0.550*	
Worthless	-0.783**	0.750**	0.441	-0.496	-0.778**	0.706**	-0.947**

***Correlation is significant at the 0.01 level (2-tailed).*
**Correlation is significant at the 0.05 level (2-tailed).*

Naturality did not correlate with beauty in this study; this could be attributed to the absence of natural mono-materials (wood, leather) in the current study. The presence of natural mono-materials familiar and desirable to consumers may have led to this relationship in the previous study (Thundathil *et al*., 2023a). While this relationship (beauty-naturality-value correlation) existed for some material samples in this study, this may be attributed to sensory similarity with natural mono-materials and no general trend was observed. The current results suggest that while natural materials could be assessed as beautiful, naturality is not an indicator of beauty. As a result, there is no general impact of naturality on aesthetic value due to beauty; however, correlations between beauty, value and strength observed in prior studies also recurred here.

Based on these findings, a modified perception framework was proposed to reflect the relationship of naturality with other core attributes (Figure 10). The qualitative data derived from the study were also added to the framework to indicate the influence of various visual and tactile stimuli in forming perceptions about multiple attributes.

The robustness of this model was inspected by recalculating the predictions based on the revised material characteristic-attribute relationships. However, this process of converting qualitative predictions to a net score and their ranking is not without issues. While it was assumed that each positive/negative characteristic is of equal weight and thus assigned equal value, the weight of attributes varies depending on the specific material-characteristic combinations. For example, fibreness in a material may be more crucial and hence carry more weight in the prediction of naturality than a characteristic like visual inconsistencies. The relative significance of visual/tactile factors in various perceptual attributes was extracted from the literature to compensate for the varying significance of material characteristics. It was observed that novelty contributed heavily to the formation of perception, especially in the case of naturality and beauty. The significance of novelty and familiarity in material perception, especially desirability, has been discussed in detail by Hekkert (2014) and Manu et al. (2022). This effect of the novelty of materials is evident from the perceptual dissonance of designers (with consumers) due to their familiarity with materials; the familiarity of materials affected all attribute ratings due to the anchoring effect. Hence, novelty has been assigned a higher weight due to its significant influence on material perception as a whole and its direct impact on individual attributes such as beauty. The role of fibreness in perceiving factors like naturality is seen in prior literature (Karana & Nijkamp, 2014), which was also established in later studies (Thundathil *et al*., 2023a). The significance of roughness/smoothness in the perception of all core attributes has been discussed extensively by Thundathil et al. (2024). The influence of the visual order of material interfaces in forming material perception (chaos-order relationship on material perception) is covered in depth in Thundathil et al. (2023b). Based on these findings, weights were assigned to the various visual/tactile characteristics identified under the perception framework (Table 5).

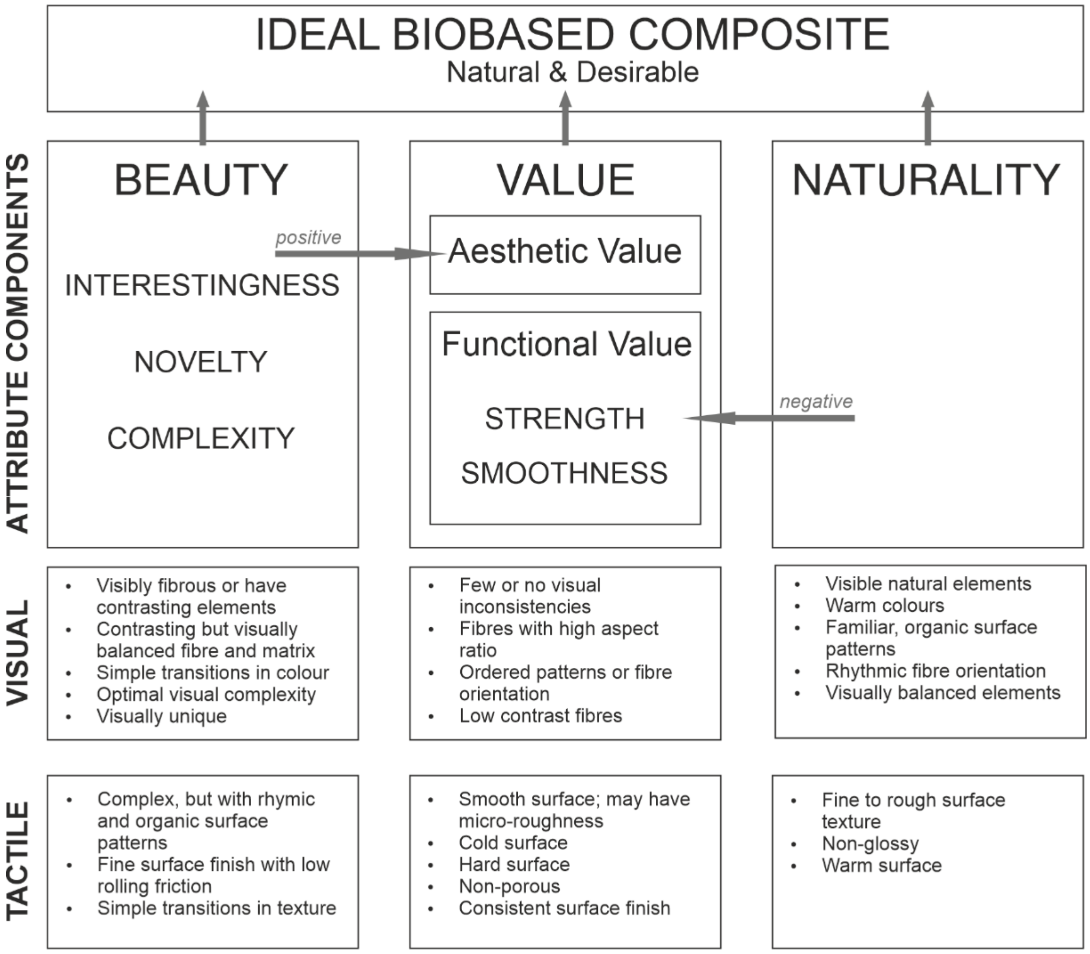

Figure 10. Modified perception framework for biobased composites

The ratings for value were observed to be heavily dependent on characteristics affecting beauty and strength, representing the two components of value from the perception framework - *aesthetic value* and *functional value*. Hence, the scorings for value were derived as a function of beauty and strength, with equal weights (value = beauty + strength). The modified predictions of material rankings (with the weights) were seen to correlate strongly with consumer survey results (Table 6), validating the biobased composite perception framework.

Table 5. Various material characteristics and weights assigned to them in the modified model

Material Characteristics	Weight
Novelty	2
Fibreness / Lack of fibreness	1.5
Randomness	1.5
Roughness / Smoothness	1.5
Visual Simplicity / Complexity	1
Coldness	1
Geometric pattern	1
Geometric, artificial texture	1
Natural particles or elements	1
Organic Patterns	1
Fibre orientation	1
Surface Hardness	1
Visual Contrast	1
Visual inconsistencies	1

Table 6. Pearson's correlation between predicted and consumer survey ranks (modified model)

Attribute	Pearson's correlation coefficient	p-value
Naturality	0.723** (0.625**) †	0.0015
Beauty	0.779** (0.680**) †	0.0003
Strength	0.770** (0.544*) †	0.0004
Value	0.733** (0.507*) †	0.0012

† Correlation Coefficient before applying weights.
***Correlation is significant at the 0.01 level (2-tailed).*
**Correlation is significant at the 0.05 level (2-tailed).*

4. Conclusion

An interesting revelation in this study was the perceptual dissonance between designers and consumers in the context of material perception. This finding is especially crucial, as the designers are expected to reflect the consumers' preferences in material selection. It is known that people use mental schema to make sense of the objects they are examining (van Rompay *et al*., 2005). They refer to their existing knowledge domain to infer the material's perceived qualities. However, familiarity with a wide range of materials and product application contexts (as in the case of designers) also biases them with a set mental schema while interacting with novel materials.

Conversely, consumers have relatively less material exposure and form novel experiences based more on their sensory stimuli. Hence, consumers' perceptions may be considered more significant in the context of materials for mass-market products, as they are the end-users and the product's success depends on their perception. This aspect also calls for a participatory design process, where consumers are involved in the material design process to validate the perceptual impact of the materials.

This study also revealed finer relationships between material characteristics and perception. In earlier studies (Thundathil *et al*., 2023b), organic patterns correlated with beauty and interestingness. However, the current study revealed that the organic pattern needs to be optimally between novel and familiar (The Most Advanced, Yet Acceptable

Principle (Hekkert, 2006)) to have the best response. A significantly novel pattern (as in the case of Kelp), unfamiliar to the consumers, was considered undesirable despite its organic origins. Another aspect was the visual contrast of fibres in biobased composites; while this factor improved the naturality of the material, it depreciated the perception of strength. While value was defined as a function of beauty (aesthetic value) and strength (functional value), consumers and designers gave significant weight to novelty and naturality while assessing value. In general, designers preferred using natural-perceived or novel materials and valued them over other materials with better beauty/strength perceptions. Hence, the perception of value in biobased composites by designers could be considered more influenced by material associations than purely by visual-tactile stimuli.

While the earlier biobased composite perception framework performed well in perception prediction, the current study further elucidated the relationship between naturality and other attributes and corresponding modifications were made to the framework with weights proposed for various material characteristics. The observation that the material perception of designers does not correlate with that of consumers makes the development of this perception framework further worthwhile. The modified perception prediction model with the proposed weights significantly improved the correlation with the actual consumer responses, pointing to a reliable model. While the applicability of this framework is limited for individual materials and contexts due to the study limitations, this could be a reliable tool in the comparative assessment (e.g., ranking) for a group of materials against various perceptual attributes. While this framework is not aimed at substituting a designer's role in material selection, it needs to undergo cross-cultural product segment tests and requires periodic updates to incorporate shifts in sociocultural trends. It can undoubtedly assist designers in their decision-making by creating a better shortlist of materials per the product's perceptual requirements. This insight is critical as biobased composites struggle with the issue of uncertain identity, as they are different from familiar materials. The high demand for such materials provides very little time for designers to map the market, and it is vital to understand how people perceive these materials. This framework can enable material designers to assess the perception of newly developed materials better and cater to consumers' material experience demands.

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Human Ethics Statement

This study was approved by the Human Ethics Committee of the University of Canterbury, Christchurch, New Zealand (HREC 2023/07/LR-PS dated 16 March 2023).

References

Berlyne, D.E. (1970). Novelty, complexity and hedonic value. *Perception & Psychophysics, 8*(5), 279-286. https://doi.org/10.3758/BF03212593

Bingham, A.J., Witkowsky, P. (2022). Deductive and inductive approaches to qualitative data analysis. *Analysing and Interpreting Qualitative Data: After the Interview*, 133-146.

Buchenau, M., Suri, J.F. (2000). Experience prototyping. *Proceedings of the 3rd Conference on Designing Interactive Systems: Processes, Practices, Methods and Techniques*, 424-433.

Carbon, C.C., Jakesch, M. (2013). A model for haptic aesthetic processing and its implications for design. *Proceedings of the IEEE, 101*(9), 2123-2133. https://doi.org/10.1109/JPROC.2012.2219831

Correa, J.P., Montalvo-Navarrete, J.M. & Hidalgo-Salazar, M.A. (2019). Carbon footprint considerations for biocomposite materials for sustainable products: A review. *Journal of Cleaner Production*, 208, 785-794. https://doi.org/10.1016/j.jclepro.2018.10.099

Haug, A. (2019). Acquiring materials knowledge in design education. *International Journal of Technology and Design Education*, *29*(2), 405-420. https://doi.org/10.1007/s10798-018-9445-4

Hekkert, P. (2006). Design aesthetics: Principles of pleasure in design. *Psychology Science, 48*(2), 157-172. http://www.pabst-publishers.de/psychology-science/2-2006/06_Hekkert.pdf

Hekkert, P. (2014). Aesthetic responses to design: A battle of impulses. In *The Cambridge Handbook of the Psychology of Aesthetics and the Arts*, 277-299. https://doi.org/10.1017/CBO9781139207058.015

Hekkert, P., Snelders, D. & Van Wieringen, P.C.W. (2003). Most advanced, yet acceptable: Typicality and novelty as joint predictors of aesthetic preference in industrial design. *British Journal of Psychology, 94*(1), 111-124. https://doi.org/10.1348/000712603762842147

Iskander, N. (2018). Design thinking is fundamentally conservative and preserves the status quo. Harvard Business Review. https://hbr.org/2018/09/design-thinking-is-fundamentally-conservative-and-preserves-the-status-quo

Karana, E., Nijkamp, N. (2014). Fiberness, reflectiveness and roughness in the characterisation of natural and high quality materials. *Journal of Cleaner Production*, 68, 252-260. https://doi.org/10.1016/j.jclepro.2014.01.001

Kastanakis, M.N., Voyer, B.G. (2014). The effect of culture on perception and cognition: A conceptual framework. *Journal of Business Research, 67*(4), 425-433.

Kouprie, M., Visser, F.S. (2009). A framework for empathy in design: Stepping into and out of the user's life. *Journal of Engineering Design, 20*(5), 437-448. https://doi.org/10.1080/09544820902875033

Lord, J., Schnarr, A. & Hutchison, P. (2009). The voice of the people: Qualitative research and the needs of consumers. *Canadian Journal of Community Mental Health*, *6*(2), 25-36.

Ludden, G.D.S., Schifferstein, H.N.J. & Hekkert, P. (2012). Beyond surprise: A longitudinal study on the experience of visual-tactual incongruities in products. *International Journal of Design*, *6*(1), 1-10. http://www.ijdesign.org/index.php/IJDesign/article/view/1036/399

Manu, T., Nazmi, A.R., Shahri, B., Emerson, N. & Huber, T. (2022). Biocomposites: A review of materials and perception. *Materials Today Communications*, 103308. https://doi.org/10.1016/j.mtcomm.2022.103308

Menninghaus, W., Wagner, V., Wassiliwizky, E., Schindler, I., Hanich, J., Jacobsen, T. & Koelsch, S. (2019). What are aesthetic emotions? *Psychological Review*, *126*(2), 171-195. https://doi.org/10.1037/rev0000135

Renoult, J.P. (2016). The evolution of aesthetics: A review of models. In *Aesthetics and Neuroscience: Scientific and Artistic Perspectives*, 271-299. https://doi.org/10.1007/978-3-319-46233-2_17

Smith, P.F. (1980). Urban aesthetics. In *Architecture for People*, 74-86.

Sparke, P., Fisher, F. (2016). *The Routledge Companion to Design Studies*. London, Routledge, 576. https://doi.org/https://doi.org/10.4324/9781315562087

Taylor, R.H. (2014). Materials selection and the stages of design: Challenging the convention. *Journal of Materials Education, 36*(6), 139-144. https://www.researchgate.net/publication/279325238

Thundathil, M., Nazmi, A.R., Shahri, B., Emerson, N., Müssig, J. & Huber, T. (2023a). Visual-tactile perception of biobased composites. *Materials, 16*(5), 1844. https://doi.org/10.3390/MA16051844

Thundathil, M., Nazmi, A.R., Shahri, B., Emerson, N., Müssig, J. & Huber, T. (2023b). Designing with biobased composites: Understanding digital material perception through semiotic attributes. *Design Science*, 9, e6. https://doi.org/10.1017/DSJ.2023.5

Thundathil, M., Nazmi, A.R., Shahri, B., Emerson, N., Müssig, J. & Huber, T. (2024). Tactility in perception of biobased composites. *Proceedings of the Design Society*, 4, 1467-1476. https://doi.org/10.1017/pds.2024.149

Tversky, A., Kahneman, D. (1974). Judgment under uncertainty: Heuristics and biases. *New Series*, *185*(4157), 1124-1131.

van Rompay, T., Hekkert, P., Saakes, D. & Russo, B. (2005). Grounding abstract object characteristics in embodied interactions. *Acta Psychologica*, *119*(3), 315-351. https://doi.org/10.1016/j.actpsy.2005.02.001

Wilson, E.O. (1984). *Biophilia*. Harvard University Press, 176.

Zingoni, M. (2019). Beyond aesthetics, empathy first. *The Design Journal*, *22*(3), 351-370. https://doi.org/10.1080/14606925.2019.1592808

Supplementary Materials

Table S1. List of materials used in the study, including key constituents and sources

Sample Name	Reinforcement	Matrix	Source
Flax UT	Unidirectional flax	Epoxy resin	Greenboats GmbH, Bremen, DE
UD Flax tape	Unidirectional Flax tape	Epoxy Resin	University of Canterbury, Christchurch, NZ + SachsenLeinen GmbH, Leipzig, DE (Flax tape)
N8010 (NABASCO 8010)	Dutch Reed fibres	Thermoset resin	NPSP BV, Amsterdam, NL
PB30XS- Brown	Bamboo short fibres	Thermoplastic Resin	MYNUSCo, Bangalore, IN
ESO- Eggy	Eggshell powder	Thermoset resin	OTTAN Studio, Istanbul, TR
N9010-Hemp (NABASCO 9010©)	Hemp and Viscose Fibres	PLA	NPSP BV, Amsterdam, NL
LA-Earth	Thermoset resin	Fallen leaves	OTTAN Studio, Istanbul, TR
Kelp	Dried kelp (*Durvillaea antarctica*) layers	Epoxy Resin	University of Canterbury, Christchurch, NZ
Scalite	Hydroxyapatite (from fish scales)	Collagen (from fish scales)	SCALE, Hasparren, FR
Sisal	Sisal fibres	Polypropylene	HSB - City University of Applied Sciences, Bremen, DE
Barktex	Barktex® fibre (from *Ficus natalensis*)	Epoxy Resin	University of Canterbury, Christchurch, NZ + Barktex, Ebringen, DE (fibre sheets)
Harakeke	Harakeke flax (*Phormium tenax*) fibres	Epoxy Resin	University of Canterbury, Christchurch, NZ
N9010-Denim (NABASCO 9010©)	Denim fibres	PLA	NPSP BV, Amsterdam, NL
Flax FE	Woven flax fabric	Epoxy resin	Greenboats GmbH, Bremen, DE
Jute	Jute needle felt	Epoxy Resin	NPSP BV, Amsterdam, NL
PB30XS- L. Brown	Bamboo short fibres	Thermoplastic Resin	MYNUSCo, Bangalore, IN

Figure S1. Image of samples mounted on 3D printed cases