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Sustainable Perspectives Using Human Beings: The Sensory Properties of a Bio-Based Material Compared to a Synthetic Material—An Overall Assessment Based on an Innovative Blind Method

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Abstract: Based on a comparative method, this paper discusses a sustainable perspective for the use of a certain bio-based material instead of synthetic materials, using human beings, with their sensory perceptions, as the central measurement tools. The innovative eco-design approaches are aimed at radical environmental improvements by focusing on the services provided to consumers. In improving the quality of a product, equity and environmental harmony have become issues and constant challenges in companies' quests for modernization. In order to achieve this goal, one of the solutions taken into account by companies in order to be increasingly competitive is to replace, sometimes partially and other times totally, synthetic materials with new non-food, bio-based materials in the manufacturing process. The approach in this paper is aimed at better integrating tactile characteristics in designing green products. The detailed review of the literature shows that a consumer's subjective perception is of paramount importance in their decision to accept a new product. Focusing on the sensory characteristics of materials with bio-based and synthetic origins, this paper draws conclusions about their resemblances and differences. The various subjective sensations when touching the two types of material are compared in order to obtain results that can protect the environment in the future.

Keywords: green material; innovation; bio-based; environment; sensory design

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Citation: Nicolau, A.-M. Sustainable Perspectives Using Human Beings: The Sensory Properties of a Bio-Based Material Compared to a Synthetic Material—An Overall Assessment Based on an Innovative Blind Method. *Sustainability* **2023**, *15*, 9145. https://doi.org/10.3390/su15129145

Academic Editor: Konstantinos S. Triantafyllidis

Received: 6 April 2023
Revised: 31 May 2023
Accepted: 2 June 2023
Published: 6 June 2023

1. Introduction

The eco-design approach aims to radically improve the environment, and it focuses on services provided to consumers, taking into account the quality, equity, and harmony that must flourish within a company [1–5]. With this in mind and in order to address these issues using methods and tools specific to sensory analyses, several research hypotheses were created. Having industrial engineering and, specifically, the product design subcategory of the general eco-design field at its core, the research presented in this paper focused on the sensory assessment of bio-based materials. These analyses were grounded in the specific knowledge, methods, and tools of engineering science, as well as in knowledge originating from the humanities and social sciences [6–13]. The first part of this paper presents the general context in which this research occurred.

This research was able to demonstrate that the present context has pushed companies to increasingly integrate a consumer's perceptions about the quality of a product and, subsequently, a consumer's overall assessment, into their approach [1,14–18]. Indeed, companies have been forced to use constant innovation in order to better meet the needs of their consumers [16]. Therefore, it has been normal for the market to be driven by technical innovation in order to develop new materials intended to replace conventional ones [19–25]. However, some of these materials, which are called ecological or green, must also meet the same technical criteria and constraints of appearance and perceived quality as the conventional ones [6,7,10–13,16,25]. This context has allowed for the introduction of a general problem, driving industry players to design new environmentally friendly products based on new environmentally friendly materials that have a perceived quality that is comparable to synthetic materials.

However, even if the quality of an objectively measured service is paramount, it is also important for a designer to be able to anticipate/predict, as much as possible, the perceived quality or value of a subjectively measured product. The human factor, in particular, knowing consumers' sensory preferences, is therefore fundamental [23,25–34]. In this context, integrating the human factor at the heart of an approach to the sensory assessment of a product is becoming a priority in the eco-design process.

In order to add to sustainable development policies, the protection of the natural environment has become a major concern in our society [25,30,33]. Given the role that companies play, the movement toward sustainable development requires that they contribute to society by developing more environmentally respectful systems via cleaner production, green products, eco-design approaches, recycling products that have reached the end of their life cycles, etc. [30,34–36]. To this end, this research study was conceived based on a series of experiments, and it was intended to ease the access of achieving the requirements mentioned above. One of the current problems for manufacturers in this field is the ability to design environmentally friendly products made from new ecological materials [35–42]. The solution was the development of "bio-based" materials. The term "bio-based" currently refers to materials with plant or animal origins [39,41,43,44]. It is hoped that, using bio-based materials, designers should be able to develop new strategies, concepts, and products that have a reduced impact on the environment [44–46].

In order to assess the ability of these materials to be suitable substitutes for conventional materials, they have been subjected to different types of evaluation [36,41,45,47]. In this research, it was demonstrated that manufacturers preoccupied with innovation are particularly interested in integrating the environmental factor. This study then analyzed how the environment can play a role in the eco-design process of developing innovative products.

The experimental validation of these various research approaches allowed us to reach a conclusion and establish to what extent bio-based materials can replace synthetic materials when evaluated via the tactile perceptions of consumers [34,38,41,48–50]. These experiments focused on two different bio-based materials from natural flax fiber (a unidirectional composite bio-based material and a twill composite bio-based material, where the orientation of the fibers was a determining factor in assessing the properties of the composites) and a third synthetic material (a composite synthetic fiberglass material). Since they have the best ratio of mechanical properties, all research and studies in the field show that flax fibers represent the main point of interest in the study of composite materials and are considered to be the most credible alternative to replace glass fibers [8].

Statistically and scientifically, glass and flax fibers have relevant resemblances [8], which led to the focus on the sensory characteristics pertaining to touch as taste and hearing were evidently excluded. With respect to smell, there was an important difference, as the flax fibers had a specific odor. Lastly, it was decided to not use sight because the difference in color between the two fiber types (the bio-based vs. the synthetic fibers) could strongly influence the subjects' preferences and, therefore, the results. In order to avoid this bias, blind tests were conducted using boxes with a special design, which are amply described in Section 2.4.

The goal of this series of tests was to determine whether the subjective sensations when touching a product made of bio-based material were similar (or not) to the subjective sensations when touching a product made of synthetic material. A majority of the results confirmed this hypothesis. Thus, out of the 10 descriptors analyzed, for a single one, a significant difference in perception was obtained.

It is worth mentioning that even though the sensory analysis method is commonly applied for assessing synthetic materials in numerous industrial fields, it remains very rarely used for assessing green or bio-based materials. The lack of theoretical knowledge is a limitation that designers face in their choice of green materials with sensory characteristics. After identifying this limitation, this study focused on the sensory assessment of certain bio-based and synthetic materials and on their resemblances and differences. Nonetheless, this research had its own limitations. One of the limitations pertained to the choice of the types of materials to be compared. Another limitation was the generalizability of the results as such a generalization was only possible for the glass and flax fibers.

2. Materials and Methods

In order to achieve a sensory characterization, the methods and tools used in sensory analyses recommend the creation of a list with suitable descriptors for assessing a material [1–5]. For these experiments, different types of materials were used. First, test boxes were created to guarantee the blind tests. Then, products were created using bio-based and synthetic materials.

For this study, bio-based materials from natural flax fibers were compared with synthetic material from glass fibers. The manufacturing process resulted in a bio-based composite material obtained from a mixture of fibers (20% flax), with a matrix of 80% resin, and a synthetic material obtained from 21% glass fiber, with a matrix of 79% resin. The orientation of the fibers was a determining factor for the composites' properties [28,35,39]. Based on the orientation of the fibers, there were two groups of semi-products: a unidirectional composite bio-based material and a twill composite bio-based material. A material is said to be unidirectional when its intertwined fibers are oriented in single direction. A material is called twill when its base fixture is made of uneven and oblique threads relative to the edges, as illustrated in Figure 1. This oblique effect was obtained by removing a thread from each line of fabric [41,42].

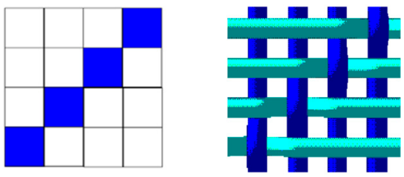

Figure 1. The shaping of the twill material.

In theory, these thread grooves should have an inclination of 45°, but in reality, this inclination varies and depends on the density of the warp and the weft. As a result, the two sides of the fabric are not identical. The warp predominates on one side, and on the other, the weft predominates [43]. For the remainder of this paper, for simplicity reasons, the term "unidirectional bio-based material" is used to refer to the unidirectional composite bio-based material, and "twill bio-based material" refers to the twill composite material.

The products were manufactured the same way for all types of materials (bio-based and synthetic). The general manufacturing protocol of the materials involved building a mold, cleaning the mold, applying an intermediary layer, applying a gel coating, cutting out the layers of flax fibers, applying the first layer of reinforcement, applying the resin, continuing with applying the layers of flax fiber and resin, and then closing the mold. In order to obtain uniform surfaces for these materials, the products were manually abraded. Different types of sandpaper were used, as was a "volume stylist," an expert in perceived quality. This qualified expert proceeded to smooth the various surfaces as, during the manufacturing process, each material type achieved a different level of rugosity (the fiberglass was smooth, the bio-based unidirectional material was grained, and the bio-based twill was ribbed). The differences in rugosity could have influenced the subjects' preferences and, therefore, the results. This bias was prevented using sandpaper in order to obtain a uniform finish for all surface types.

In the field of computer equipment, for tools such as keyboards or mice, it is important to take into account the tactile sensory dimension. Indeed, a consumer's hand is in constant contact with a keyboard or a mouse; therefore, the tactile modality is constantly solicited.

The user's sensation during this interaction with equipment can influence their purchasing behavior, their rate of use, etc. [1,3,14,15]. For this reason, it appeared relevant to assess a user's sensations when touching a product in the shape of a computer mouse. To this end, for each type of material, a standard size mouse shape was created, though the samples had different finished surfaces. A summary is provided in Table 1.

Table 1. List of finished surface products (mouse-shaped).

Type of Fabric	Surface Variation	Identical Products	Abbreviations	Product
Twill bio-based material	1	1	Product-1	
Unidirectional bio-based material	1	1	Product-2	
Synthetic fiberglass material	1	1	Product-3	

2.1. Creating the List of Descriptors

Perception and its understanding are complex issues that begin with defining the vocabulary to be used. It is often difficult to accurately define one's sensations, especially for touch [5]. Unlike vision, touch is not a sense generally used to describe our environment. In order to define a unique sensory vocabulary for a given population, a psycho-physical approach was used. Several psychological studies have attempted to determine what descriptive words (descriptors) could be used for the sense of touch and, especially, for the sensations related to textures [12,14,17–19]. A descriptor is a term that is defined as precisely as possible to describe a sensation, and its role is to be understood in a homogeneous way by all subjects.

To be effective, a descriptor must meet three basic requirements: relevance, precision, and differentiation, and to a lesser extent, it has to be exhaustive and independent [4–6,9–12]. This study began with a list of 10 descriptors from the literature [50–52]. This list is presented in Figure 2. Based on this list of descriptors, this study focused on consumers' sensations.

2.2. Panel Selection

Building on the work of Pensée Lhéritier [52], this research was first conducted without any bibliographical reference. Therefore, it was accepted that the panelists would work without specific instruction, and the consumers would use their own personal frame of reference when evaluating the products. This approach meant that the panel of selected subjects would also be unknowledgeable about the specifics of the materials.

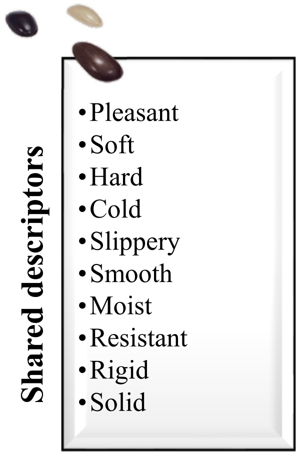

Figure 2. The list of shared descriptors for all material types.

It should be noted, however, that consumers' interpersonal differences led to differences not only in their preferences but also in the intensity of their preferences. The same product was perceived differently by the different individuals. Numerous studies have sought to explore the influence of personal characteristics on consumers' preferences regarding choice [2,9,11,12,15,18,21,22]. Thus, when a panel is not homogeneous, there is a risk of obtaining divergent information that is unusable for a sensory designer. The results of a study intended to assess the perceptions of a group of consumers are influenced by the number and nature of the subjects tested—the more the individuals share similarities, the more their perceptions of a given product will tend to be similar. It is therefore essential to specify a target population as precisely as possible in order to increase the likelihood of creating a good rapport between the tangible attributes of a product and the consumers' perceptions [11,21,22]. The sample of subjects in this study was representative of a general target population educated in using a PC mouse, and this was the reason why the product used in this research was created in the shape of a PC mouse.

As such, a group of 18 people—7 women and 11 men—was selected. They were recruited from students in the EDIM Department (Ergonomics Design and Mechanical Engineering) of the UTBM (University of Technology Belfort Montbéliard), comprising French subjects between 20 and 22 years old. This type of recruitment guaranteed the abovementioned homogeneity of the population in terms of age, background, and level of knowledge in the field of sensory design.

2.3. Tactile Exploration of the Samples—Actual Proceedings

The literature agrees that movement is essential for the perception of texture. There are many ways to manipulate products in order to perceive their tactile properties, including tangential touch, orthogonal touch, and static touch, as well as lateral friction, wrapping, and encompassing movements [3–5]. Lateral friction, wrapping, and encompassing are movements that provide information about the shape, size, and weight of a sample [6]. As part of the experiments, there was particular interest in gathering information about the surfaces of the samples. Therefore, only the first three types of touching movements were used.

The subjects had to execute these three types of touching movements either with their index fingers, middle fingers, or ring fingers using only the first two phalanges of each finger. The subjects could not manipulate the samples. Each of these three actions had to be performed three times on each product. The gestures made were as follows: a tangential touch, an orthogonal touch, and a static touch. For the tangential touch, the fingers moved quickly on both sides of the surface, as shown in Figure 3. For the orthogonal touch, the fingers applied pressure on one part of the object while another part of the object was kept stable, as shown in Figure 3.

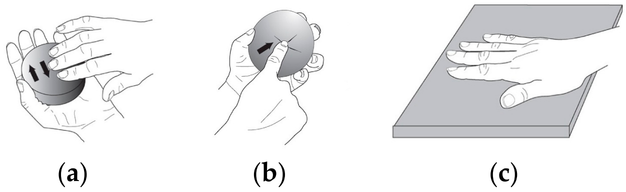

Figure 3. Types of movements. (**a**) tangential touch, (**b**) orthogonal touch, and (**c**) static touch.

For the static touch, the hand was placed on a part of the object without any particular movement, as shown in Figure 3. The order of these three touching movements was interchangeable from one subject to another. Thus, each subject had to follow a defined order for touching the sample products.

2.4. Blind Tests—Box Construction

The experiments were conducted blindly in order to minimize the impacts of other sensorial modalities on the results. To this end, a test box painted in black was built, as shown in Figure 4.

Figure 4. Presentation of the box used for assessing the products during the experiments.

The box allowed the subjects to evaluate the three mouse-shaped objects. The box had three openings, allowing each subject easy access to the products. The openings were specifically dimensioned to allow direct and single access to the products, facilitating the types of touching movements defined under this protocol and mentioned above.

The mouse-shaped objects were glued to the bottom of the box, and this did not allow the subjects to manipulate or move them, as it was intended to facilitate only the types of touching movement selected for this assessment. Figure 4 shows the steps of the blind tests.

2.5. The Steps of the Experiments

All the subjects selected for the experiments were invited to a classroom used especially for this series of tests. The experiment was guided and supervised by an experimenter. After presenting the general guidelines, the experimenter continued with a five-minute collective video projection with verbal explanations about the required behaviors during the experiment. Following this presentation of the instructions, the experimenter distributed a test sheet containing a table with the list of descriptors.

The list of established descriptors was presented in the form of a Likert scale, as shown in Figure 5. This scale was ordinal, and the possible answers to questions were arranged hierarchically [5,13,21,52]. The different product categories (twill bio-based material, unidirectional bio-based material, and synthetic fiberglass material) were not disclosed in order to ensure consistency. Therefore, the semantics regarding the product categories did not influence the ranking that the subjects chose [53,54]. Using the test sheet presented in Figure 5, for each descriptor, a subject had to indicate their degree of preference according to the grid from 1 to 5, thus assessing their perceived sensation when touching a product. A rating of 1 meant that the descriptor was in perfect agreement with their sensation when touching the product, and 5 meant that the descriptor was in complete disagreement with their sensation when touching the product.

The descriptors	Product 1				
	1 - Agree	2	3	4	5 - Disagree
Pleasant	1	2	3	4	5
Soft	1	2	3	4	5
Hard	1	2	3	4	5
Cold	1	2	3	4	5
Slippery	1	2	3	4	5
Smooth	1	2	3	4	5
Moist	1	2	3	4	5
Resistant	1	2	3	4	5
Rigid	1	2	3	4	5
Solid	1	2	3	4	5

Figure 5. The test sheet (ordinal scale).

After touching the products, the participants assessed their sensations according to test grids in conformity with the established list of descriptors. There was no time limit imposed to complete the experiment. Although it was a typical product in the shape of a computer mouse, the subjects were asked not to take it in their hand or hold it, but instead to strictly examine it according to the previously defined touching movements (tangential, orthogonal, and static) using only one or two fingers.

2.6. Result Analysis and Statistical Tools

The goal of this series of tests was to measure and then compare the subjective sensations related to each of the descriptors ascribed to the different types of materials.

First, for each subject and descriptor, two different scorings were created. For practical reasons (in order to simplify the quantification of the results), the scorings assigned to each descriptor were summed based on material type (bio vs. synthetic), without taking into account the surface variations and types of movement involved in touching the samples. Therefore, for each subject, two scorings were obtained for each descriptor: a scoring corresponding to the subjective sensations when touching the unidirectional and twill bio-based materials, and a scoring corresponding to the subjective sensations when touching the synthetic material.

Based on the calculus method, the scores obtained for bio-based materials were then reduced (divided by 2, as this represented twice as many samples in the case of the synthetic materials) in order to create a scale similar to the one obtained in the case of the synthetic material.

The second step was to create two other complementary scorings: one corresponding to the subjective sensations when touching the unidirectional bio-based material, and another corresponding to the subjective sensations when touching the twill bio-based material. These two scorings were calculated by adding the values assigned to each descriptor for the two bio-based materials.

In order to analyze these different scorings, the Student Replicate Test (a software tool) was used, and it repeatedly measured the subjective sensations that each subject, following the descriptors list, expressed when touching the products.

The Student Replicate Test compares the mean values of two populations and creates a direct rapport between the characteristic of one population and a characteristic of the other. The Student's test, or t-test, a tool based on a parametric hypothesis, is able to obtain a statistic calculus following a Student law. When, based on the equivalence of the mean values, a Student law hypothesis is null, then that hypothesis is true.

With the help of Student Replicate Test, a subjective sensation was coded as an Observation, and these Observations were correlated as Pairs.

If we let xij represent the Observation j for Pair i (j = 1, 2 and i = 1, 2, . . . , n), then for each pair of observations, the difference is calculated as di = xi2 − xi1.

The statistical test is defined by:

$$t\_observed = \frac{\overline{d}}{\sqrt{\frac{S_{d^2}}{n}}} \quad (1)$$

where n is the number of pairs of observations, $\overline{d}$ is the average of the differences between the observations, and $S_d{}^2$ is the variance.

The relationship between a statistical hypothesis and *t_observed* is available in a table generated by Student Replicate Test.

The null hypothesis, known as the equivalence of the means, is rejected at the significance threshold, noted as p, if:

$$|t\_observed| > t_{n-1,1-p/2}, \quad (2)$$

where $t_{n-1,1-p/2}$ is the value available in the table for the degree of freedom $n - 1$ (note that the degree of freedom was considered as the strict interval defined by the sensory profile obtained based on the list of descriptors).

Traditionally, the statistical software indicates three types of data: the value of the calculated t, the number of degrees of freedom considered ($n - 1$), and the significance threshold, which is noted as p. Therefore, if $p \leq 0.05$, then the null hypothesis is rejected, and we can conclude that there was a significant difference in the mean values; if $p > 0.05$, then the null hypothesis is accepted, and we cannot conclude that there was a significant difference in the mean values.

3. Results

The results of this experiment led to the identification of a descriptor for which there was a difference between the subjective sensations when touching the bio-based vs. synthetic materials. Table 2 and Figure 6 present a summary of all the results.

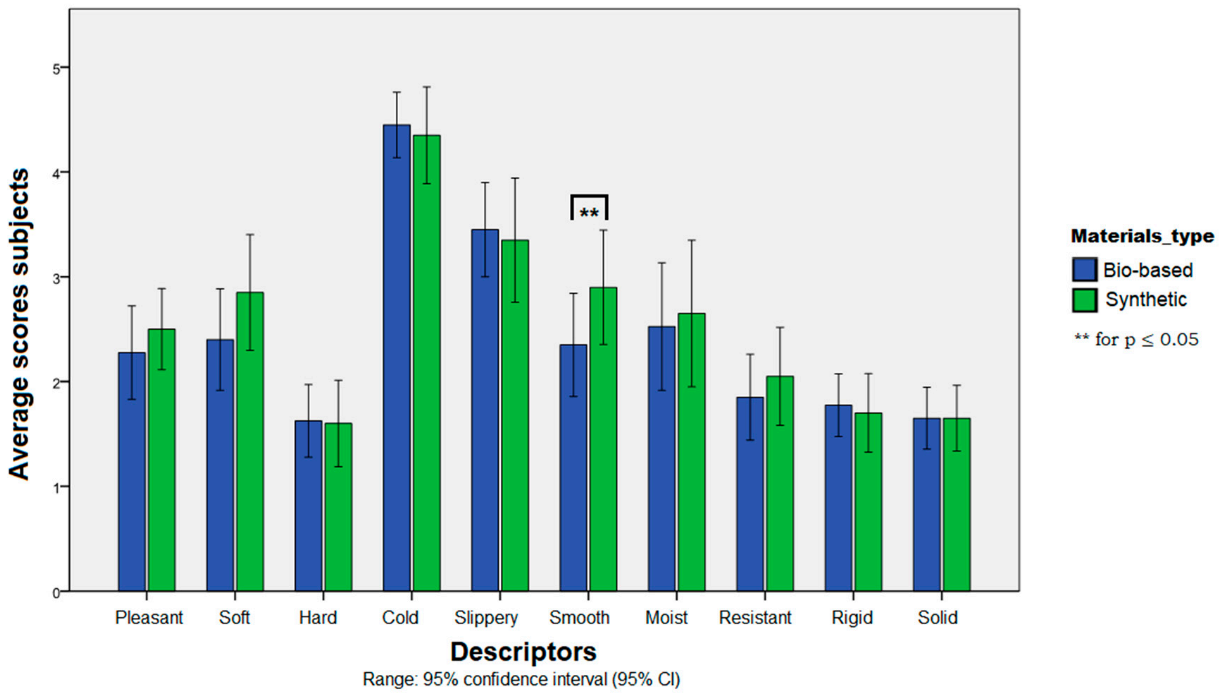

Figure 6. Trustworthy intervals: bio-based vs. synthetic materials.

Table 2. Results: bio-based vs. synthetic materials.

Results Bio-Based vs. Synthetic Materials						
Descriptors	**Material**	**Mean**	**Standard Error**	***t***	**ddl**	***p***
Pleasant	Bio-based Fiberglass	2.23 2.50	0.18 0.19	−1.26	19	≥0.05
Soft	Bio-based Fiberglass	2.40 2.85	0.23 0.26	−1.71	19	≥0.05
Hard	Bio-based Fiberglass	1.63 1.60	0.17 0.20	0.15	19	≥0.05
Cold	Bio-based Fiberglass	4.45 4.35	0.15 0.22	0.72	19	≥0.05
Slippery	Bio-based Fiberglass	3.45 3.35	0.21 0.28	0.43	19	≥0.05
Smooth	Bio-based Fiberglass	2.35 2.90	0.24 0.26	−3.32	19	≤0.05
Moist	Bio-based Fiberglass	2.53 2.65	0.30 0.33	−0.46	19	≥0.05
Resistant	Bio-based Fiberglass	1.85 2.05	0.20 0. 22	−0.97	19	≥0.05
Rigid	Bio-based Fiberglass	1.78 1.70	0.14 0. 18	0.77	19	≥0.05
Solid	Bio-based Fiberglass	1.65 1.65	0.14 0.15	0.00	19	≥0.05

It became obvious that for descriptors such as "Pleasant," "Soft," "Hard," "Cold," "Slippery," "Moist," "Resistant," "Rigid," and "Solid," there were no differences in the subjective sensations induced by touching the different types of materials, whether they were the bio-based or synthetic materials. Only the results related to the "Smooth" descriptor indicated that the subjective sensations were different. This specific result is indicated in red in Table 2.

The similarities and the differences between the two types of bio-based materials (unidirectional and twill) vs. the synthetic material were explored. In this context, only those descriptors that showed a significant difference between the bio-based materials as a whole and the synthetic one received attention. The results obtained for the subjective perceptions when touching the twill bio-based material compared with the synthetic material are shown in Table 3.

Table 3. Product results: twill bio-based material vs. synthetic fiberglass material.

Results Twill Bio-Based Material vs. Synthetic Fiberglass Material						
Descriptors	**Material**	**Mean**	**Standard Error**	***t***	**ddl**	***p***
Smooth	Twill Fiberglass	2.30 2.90	0.30 0.26	−2.26	19	≤0.05

The results obtained for the subjective perceptions when touching the unidirectional bio-based material compared to the synthetic material are shown in Table 4.

Table 4. Results: unidirectional bio-based material vs. synthetic fiberglass material.

Results Unidirectional Bio-Based Material vs. Synthetic Fiberglass Material						
Descriptors	**Material**	**Mean**	**Standard Error**	***t***	**ddl**	***p***
Smooth	Unidirectional Fiberglass	2.40 2.90	0.26 0.26	−2.26	19	≤0.05

The results obtained for the unidirectional and twill materials were similar to those obtained for the bio-based materials as a whole. In conclusion, only a synthesis of the significant differences between the subjective sensations when touching the bio-based materials as a whole and the subjective sensation when touching the synthetic material are presented. This summary is shown in Figure 7.

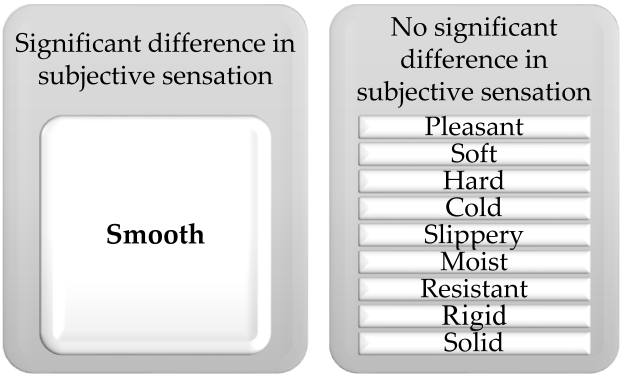

Figure 7. Synthesis of the significant differences in the subjective perceptions.

This sensory methodology aimed to use the subjects as real measuring tools. The goal of this research was to understand, interpret, and control the criteria of the perceived qualities in order to achieve to a better tactile sensation in terms of the perceived qualities of bio-based materials. This assessment had the particularity of being completely subjective, even though a methodology based on human evaluation is not without difficulties for delivering solid results.

The discussion in this paper aimed to position sensory design and its associated methods (sensory assessment) in the larger approach of the choice of materials in the process of product design. Sensory design can be seen as a resource that, with the help of sensory profiles, can support the choice of materials.

In terms of originality, the first advantage of this work was its use of a sensory assessment of a bio-based material with the objective of finding a minimum number of descriptors (shared lists for the materials studied) that were able to provide maximum information about the sensory properties of the bio-based material being analyzed. The second originality advantage of this work was that it measured the intensity of the perceived sensations when touching a bio-based material, considering each of the selected descriptors. The third originality advantage of this work was that it created, based on all the descriptors, the sensory profile of a bio-based material made of flax fiber.

4. Conclusions

The tactile sensory assessment method carried out with the help of a panel of subjects provided the means to explain how it can be possible to predict the perceived quality of a material when, very early in product design, a consumer's preferences are taken into account. In addition, the methodology used—incorporating the simple tool of a sensory assessment, as described above—is an asset for the design field, especially for visionaries, ergonomists, and designers preoccupied with saving and protecting the environment.

This research focused on the sensation felt when touching a bio-based material. As with conventional materials, the goal of this research was to define suitable methods and tools that, based on sensory analysis, aim to describe, with a minimum number of words and a maximum level of efficiency, various products made of bio-based materials. The goal was to provide an improved tool that is precise, reproducible, and easy to understand. This practical approach, carried out in the field of sensory assessment, allowed us to present the contribution that could be made based on the methodology proposed for taking into account consumers' preferences upstream of the process of designing products made of natural fibers. In conclusion, these results indicate that there are no differences in subjective perceptions when touching a product made of a bio-based material vs. one made of a synthetic material.

The contribution of this research, based on the feedback obtained from all the tests presented, introduces an original methodology of sensory assessment with a human being as the measurement tool in order to develop an instrumental evaluation. The products in this study—bio-based materials (made of flax fibers) and conventional materials (made of glass fibers)—have the potential to be interesting space-products in terms of subjective perceptions and in terms of environmental design.

Finally, one of the possible future directions detached from this research study is to replicate this experiment using other material types. Another direction could be aimed at replicating the experiment in cultures different than the studied European culture (e.g., Japanese, African, etc.). A possible third direction to be taken into account is to replicate the research using artificial intelligence.

Funding: This research was funded by the Romanian Ministry of Education and the University Politehnica of Bucharest through the PubArt Program.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The author declares no conflict of interest.

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