

Article

Kansei Drives Sustainable Material Innovation—An Approach to Enhance the Added Value of Biomass Materials

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Abstract: In this study, we discovered that the physical composition of materials can significantly affect users' psychological and physiological responses. Materials research constantly offers novel materials as better alternatives to convention. However, the functionality of a material no longer ensures its commercial success and widespread use. Additionally, the material should provide significant added value beyond its practical evaluation. Kansei, a concept derived from the Japanese language, pertains to the psychological perception of a product's functionality and has attracted considerable attention in both industry and academia. This study proposes a Kansei-driven sustainable material method to enhance materials' added value. We quantified users' Kansei of tea waste materials via experiments. Specifically, we first measured the physical qualities of the materials, such as their color, surface roughness, and odor index. Next, we used semantic differential and pairwise comparison methods to measure users' impressions and preferences toward the materials. We also employed wearable physiological measurement devices to capture users' reactions to the materials, including the skin conductance level (SCL) and heart rate (HR). Finally, we conducted correlation analysis using the Statistical Package for the Social Sciences (SPSS) on the collected physical, psychological, and physiological data. This study found strong correlations between the materials' frictional coefficients and surface roughness and people's psychological evaluations, such as sensory and safety factors. In addition, we also found that these physical qualities affect people's HR and SCL, leading to changes in people's emotions. These findings carry significant implications for enhancing the added value of materials.



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Keywords: biomass materials; Kansei; Kansei evaluation; physiological measurement techniques

1. Background and Purpose of the Study

The problems of global warming, environmental degradation, and petroleum scarcity have spurred research on sustainable resources. Biomass is an essential sustainable resource, like wind, solar, and geothermal energy, with the characteristic of being inexhaustible [1]. Biomass energy technologies include biomass power generation, bio-liquid fuels, biogas, solid-formed fuels, and biomass materials. Biomass materials are industrial products and raw materials from biomass, such as paper, wood, and leather. Unlike traditional polymer materials, biomass materials are green, environmentally friendly, renewable, and biodegradable. Scholars believe that biomass materials are the core of a circular society [2]. Due to progress in the physicochemical research of biomass materials, they have been widely applied in packaging, construction, textiles, and other fields [3–5]. For example, IKEA has developed new furniture packaging materials such as mushroom foam, honeycomb core materials, sugarcane thin layers, and molded paper molds, achieving record-breaking sales while reducing carbon emissions.

Although biomass materials have been the subject of decades of research, they are still in the early stages of commercial development [6]. While researchers typically focus on improving material properties, other factors hinder the commercial success of biomass materials. Consumers generally hold a negative opinion of biomass consumer goods,

considering them poor quality, cheap, and not durable. We conducted an experiment on material preference, in Figure 1, regarding the two wooden materials shown; although both are natural wood, more people prefer the wood on the left, considering the one on the right to be cheaper and of lower quality [7]. The material on the right is oriented strand board (OSB), a wood material with good mechanical properties. However, due to the processing method, the raw material has an irregular distribution, forming a distinct contrast with the smooth texture of wood, and, as such, is often misunderstood as a waste material [8]. The price of wood is several times that of oriented strand board. These examples show that people's evaluation of materials greatly influences their commercial success. Existing research must delve more into the importance of customer evaluations in material development. Therefore, this article will focus on the relationship between the composition of biomass materials and people's evaluation, explore factors that affect evaluation, and provide new research approaches to support the commercial success of biomass materials.

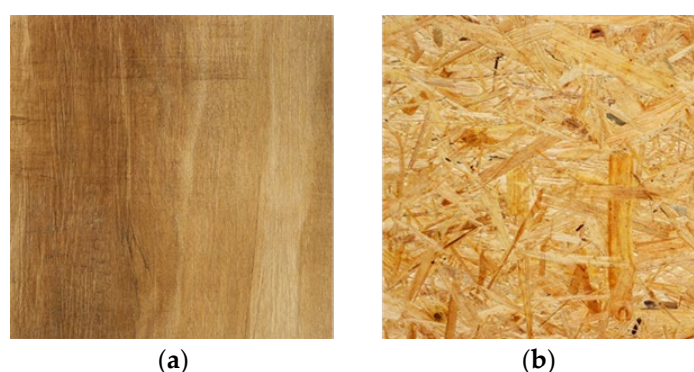


Figure 1. (a) Wood; (b) wooden oriented strand board.

In the commercial field, biomass particleboard application is an example of using abundant plant fibers in biomass materials to make particleboards, which are further processed into panel furniture [9]. However, during the manufacturing process, adhesives must be added to improve the mechanical properties of the particleboard. These adhesives contain a large amount of formaldehyde, and exposure to a formaldehyde environment can irritate the eyes, nose, and throat, causing symptoms such as tearing, sneezing, coughing, and even vomiting [10]. Consequently, concerns about formaldehyde can lead to negative evaluations of biomass materials. Additionally, common biomass materials such as wood chips, rice husks, and straw have irregular shapes, and the surface texture after processing is irregular. Although this irregularity does not affect the material's functionality, it significantly reduces people's evaluation.

For a new material to succeed in the market, besides its functionality, developers must also consider the feelings it evokes in people. The aesthetic part of product appreciation stems from the characteristics of the material, which define the appearance of the object and generate emotional responses that can influence purchasing behavior [11]. Recent research indicates that the attractiveness of materials depends on their semantic, expressive, sensory, and emotional attributes, which are considered essential components of purchase decisions [12]. Therefore, materials' sensory, expressive, and emotional dimensions are essential to their practical applications.

Currently, most biomass materials are still in the early stages of the consumer goods market, like the initial perception of plastics as cheap, low-quality, and artificial [13]. Although the invention of plastics has played an essential role in various fields and human society's progress, plastic products initially needed to be more satisfying. To change the negative impression of plastics, people often used decorative veneers of natural materials such as imitation wood and marble on the surface of plastic products [14].

In the 1950s, Tupperware developed a lightweight and flexible new plastic (mainly composed of polyethylene resin) that was significantly different from other plastic products.

These products retained the physical properties of plastics while bringing users a completely new experience [15]. This new experience made Tupperware products indispensable in modern kitchens (Figure 2). Therefore, changing the material's texture can change people's evaluation and drive commercial success.



Figure 2. Tupperware product poster from the 1950s.

The 'intuition and perception' of users toward the material characteristics of an object is a vital aspect to consider when designing it. Based on the case of Tupperware, researchers have pointed out that new materials need to meet functional requirements and prioritize the user's sensory experience with the material [16–18]. Kansei is considered an effective method for improving a material's overall experience. Derived from the Japanese language, Kansei refers to the psychological perception of a product's functionality and has garnered wide attention in both industry and academia [19]. In materials, researchers such as Zhao Yanyun suggest that Kansei can assist designers in accurately grasping users' evaluations of product materials, resulting in products that offer better user experiences [20]. A study by Suda Takashi et al. demonstrated that Kansei can extract user Kansei data on different materials, propose design focal points, and alter people's perception of traditional plastic as cheap [21]. An increasing number of researchers believe that endowing materials with Kansei as an added value distinguishes them from other materials, enhancing people's evaluations of the materials and promoting the idea that a more comprehensive application is possible.

Kansei's research encompasses four main aspects: (1) perceiving users' Kansei data, (2) defining the design characteristics of the product, (3) predicting and establishing a relationship model between users' Kansei data and product features, and (4) optimizing product design [19]. Acquiring and categorizing users' Kansei data is central to Kansei research [22].

However, there are still challenges in the current methods used for acquiring Kansei data. Kansei evaluation serves as a primary means in Kansei research, and existing studies have divided Kansei evaluation into two main dimensions: impression and preference [21,23–28]. Researchers often commit to improving people's impressions and preferences rather than studying the relationship between impressions and preferences, including in cases where impressions and preferences are confused and inseparable. Impression and preferences differ in definition, measurement methods, and Kansei value level, aspects which we will discuss further below.

Using product images as experimental stimuli, Kamata Akiko et al. verified and analyzed the relationship between impression and preference [29]. Experimental results showed that commodities with high impression evaluation scores were likely to be selected, though they did not show significant results. However, the experimental results also showed high impression evaluation scores but low preference evaluation scores [29]. Our previous studies have confirmed this result by analyzing the relationship between people's impressions and preferences using images of recycled materials from tea waste [30]. The research findings indicated a positive correlation between impression evaluation words such as natural, bright, and warm and preference. However, positive impressions such

as gorgeous and eye-catching negatively correlated with preference [30]. These results suggest that improving impressions does not necessarily lead to improving preference.

The construction of the Kansei Value Model is crucial for product design and consumer experience. Based on previous research findings, the construction diagram (Figure 3) [31–34] reveals a certain level of consistency in the lower and middle layers. However, some differences exist in the upper layer's construction. Researchers made this model based on the theory of personal construct psychology, which suggests that everyone has a hierarchical structure of cognitive units, processing information from bottom to top to determine behavior [34]. Some studies consider 'attitude' and 'value' as the primary evaluation items in the upper layer's construction.

In contrast, others focus on 'preference' within the 'behavior' category as the primary evaluation criterion. Therefore, we can infer that 'preference' plays a vital role in the upper layer of the Kansei Value Model. In design activities, designers often rely on the 'impression' in the middle layer of the model to guide their design process. However, conducting preference research alone may not directly guide design activities. Conversely, more than focusing on impression research, neglecting preference research may lead to a disconnect between designers and user groups. Therefore, to simultaneously meet user preferences and the needs of design activities, it is crucial to adopt design methods that can enhance impression and preference. Taking into account user preferences and impressions can assist designers in creating products that better meet user needs and expectations, thereby improving the market competitiveness and user satisfaction of the products.

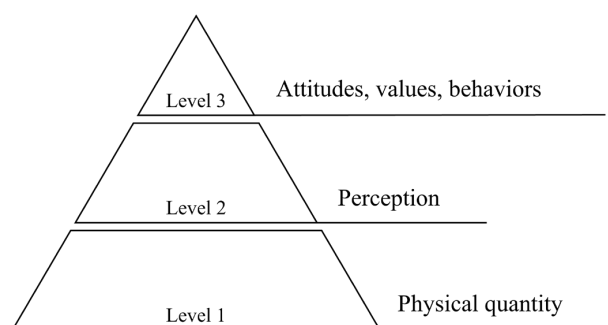


Figure 3. Kansei value-hierarchy model.

Furthermore, regarding the dimensions of Kansei evaluation, research primarily focuses on a single dimension (such as visual or tactile). Although humans obtain 78% of information through visual perception (which, to some extent, determines the importance of visual dimension in sensory evaluation), the integration of auditory, tactile, olfactory, and gustatory senses contributes to users' perceptions and experiences of tangible and intangible products, playing a role throughout the entire process of purchase and consumption. The five senses carry different weights in users' experience, and all play significant roles [35], with their combined influence surpassing their contributions [36]. Additionally, studies have indicated that the semantic content of sensory evaluations obtained from individual or multiple senses differs when evaluating the same sample [37]. Currently, research on the Kansei evaluation of biomass materials primarily focuses on visual perception, while utilizing the other four senses has yet to be fully explored.

With this background, this study aims to propose a method driven by Kansei to promote sustainable material innovation and evaluate the relationship between the physical composition of materials and users' Kansei. Figure 4 illustrates the proposed research methodology model. The model quantifies the elements of physical quantity and Kansei value and then analyzes their relationship separately. Compared with previous models, this model aims to improve the impression and preference of the experimental subjects simultaneously by redesigning the experimental samples, its main feature.

The first step of our research was to determine the physical qualities of sustainable materials. In the second step, we conducted experiments that integrated visual, tactile,

and olfactory senses to analyze the influence of sample physical qualities on users' Kansei, including their impressions and preferences. Researchers have also found that materials can impact users' emotions, influencing their acceptance of products [38–41]. Researchers utilized physiological measurement techniques to analyze the relationship between wood, linen, canvas, and wool material properties and users' pleasant emotions [42]. However, in the field of biomass material research, there currently needs to be more research applying these techniques to analyze the emotional aspect. Therefore, in our study, we also consider users' emotions and analyze the impact of material physical qualities on users' emotions using relevant physiological measurement techniques. In this research, we aim to identify physical qualities that effectively enhance the Kansei value of sustainable materials and provide quantitative guidance for the reuse of sustainable materials in the future. This study offers several innovative aspects for enhancing the Kansei value of biomass materials: 1. utilizing multiple sensory dimensions synergistically for measurement; 2. integrating impressions and preferences for Kansei evaluation; and 3. using research methods related to emotional measurement to conduct Kansei evaluations at the Kansei and physiological levels.

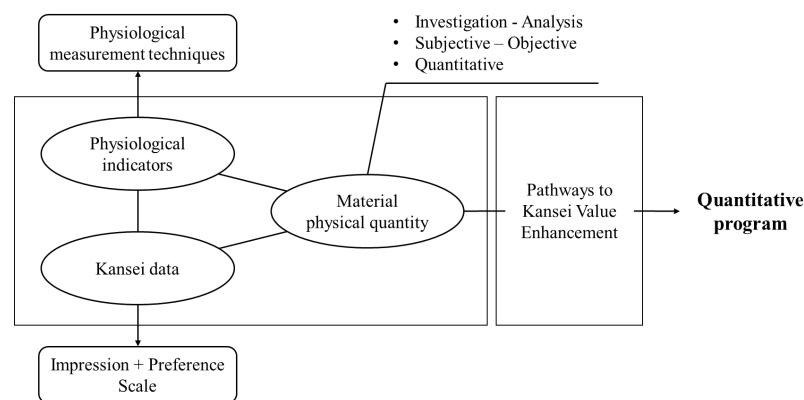


Figure 4. Research model structure diagram.

This article is organized as follows: In the second part, we present the experimental methods and procedures for the Kansei evaluation of biomass materials, providing a detailed description of the measurement methods used to determine the physical qualities of biomass materials and various user Kansei indicators. The third part presents the experimental results and discusses approaches to enhance biomass materials' Kansei value based on the experimental findings. Finally, we conclude the paper.

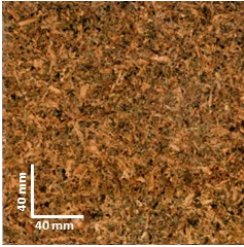
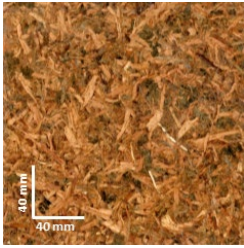
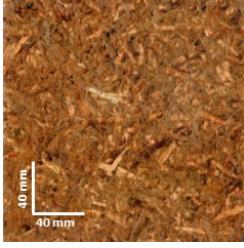
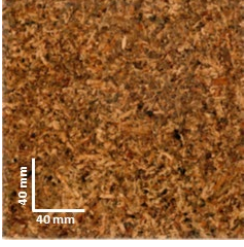
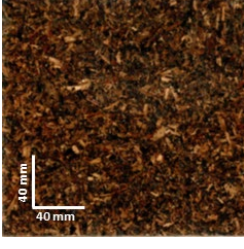
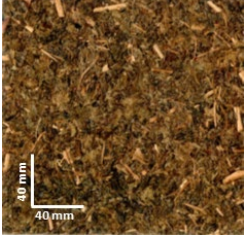
2. Kansei Evaluation and Methods

2.1. Production and Measurement of Biomass Materials

We used tea waste as the material in this experiment. Tea waste mainly consists of tea residues and tea stems, which are underutilized waste products. With the increase in tea production and the widespread adoption of mechanized tea-harvesting techniques, the amount of tea waste generated is becoming a significant problem. We used tea waste's plant fiber-rich nature and subjected it to high-temperature hot pressing to form it into shapes. In mechanical testing, we found that tea waste exhibits good mechanical strength and rapid biodegradability [30,43], making it a noteworthy sustainable material. In addition, unlike other biomass materials, tea waste originates from tea, and the formed material has a distinct tea aroma, a significant characteristic that sets this material apart. The noticeable tea aroma can better stimulate people's olfactory senses, meeting the requirements of our research from a multisensory perspective. Therefore, in this experiment, we used different types of tea waste (black tea stems, green tea stems, oolong tea stems, and tea residues produced in Anxi, Fujian) and processed them through various degrees of grinding and hot pressing to create the samples for this experiment (Table 1). Subsequently, we used

a laser engraving machine to cut tea waste samples into uniform dimensions (80 mm in length, 80 mm in width, and 3 mm in thickness) for subsequent experiments.

Table 1. Tea waste artificial material samples.

Serial Number	Sample Composition and Processing	Sample Chart
Sample 1	Oolong tea stems (variety: Jinjunmei), 2 crushing process iterations, then the material was sieved with a sieve of 40 mesh or higher for hot pressing	
Sample 2	Oolong tea stems (variety: Jinjunmei), pulverized once and hot-pressed	
Sample 3	Oolong tea stems (variety: Iron Goddess of Mercy), pulverized once and hot-pressed	
Sample 4	Oolong tea stems (variety: Jinjunmei), 2 crushing treatments and sieved with a sieve higher than 80 mesh for hot pressing	
Sample 5	Black tea stems (variety: Zhengshan Xiaojiao), 1 crushing treatment and hot pressing	
Sample 6	Green tea dregs discharged from beverage factories without sub-crushing treatment; the material was directly used for hot pressing	

To measure the samples' physical properties, we aligned the measurements with three sensory dimensions of human perception (Figure 5). Firstly, we used a spectrophotometer, NIPPON DENSHOKU NF-333 (Tokyo, Japan), to measure the L^*C^*h (for L^*C^*h color space, the L^* indicates lightness, the C^* is the chroma axis, and h is the hue angle) of the samples, which primarily corresponds to the visual evaluation dimension of users. Since the color of the samples is not uniform, we selected four endpoints and the center point of the samples for measurement and took the average value. During the measurement, we set the light source to standard light D65 and the angle to 10° . Next, we used a surface texture tester, the KES-FB4-A by KATOTEC (Kyoto, Japan), to measure the MIU (mean friction coefficient: the smoothness perceived by individuals when touching a surface), MMD (mean deviation of the friction coefficient: the perceived smoothness or roughness when touching a surface; a higher MMD value indicates a rougher surface), and SMD (mean deviation of surface roughness: average deviation of surface unevenness data), which primarily corresponded to the tactile evaluation dimension of users. Finally, we used an odor analyzer, the COSMOS—XP-329IIIR (Tokyo, Japan), to measure the odor concentration index of the samples, reflecting the evaluation of users at the olfactory level. The selected samples were placed in a ventilated area to ensure unbiased evaluation and remove any noticeable odor. Subsequently, we applied different concentrations of tea tree essential oil to the sample surfaces to give the samples the same type of odor but with varying concentrations.

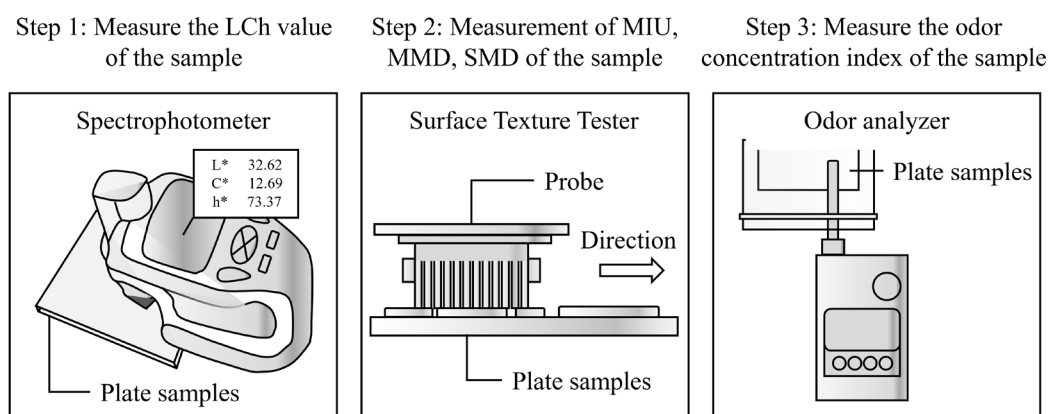


Figure 5. Schematic diagram of equipment used for measurements.

2.2. Experimental Environment

The location of this experiment is the Product Design Laboratory of the Cheung Kong School of Art & Design of Shantou University in Shantou city, Guangdong province, China (Figure 6). In the laboratory, we turned on the air conditioning to maintain the temperature and humidity within the range of $22 \pm 2^\circ\text{C}$ and $40\% \pm 10\%$, respectively. To stabilize the light source, we placed the experimental samples inside an international standard light source box (3nh DOHO) and set the internal light source of the box to D65. We conducted all subsequent experiments inside the light source box. We placed whiteboards around the experimental table to prevent the laboratory environment from affecting the participants' visual perception. Throughout the experiment, the participants sat about 45 cm from the light source box. We placed two laptops next to the light source box, one recording the participants' Kansei evaluations of the samples and the other recording the participants' physiological data.

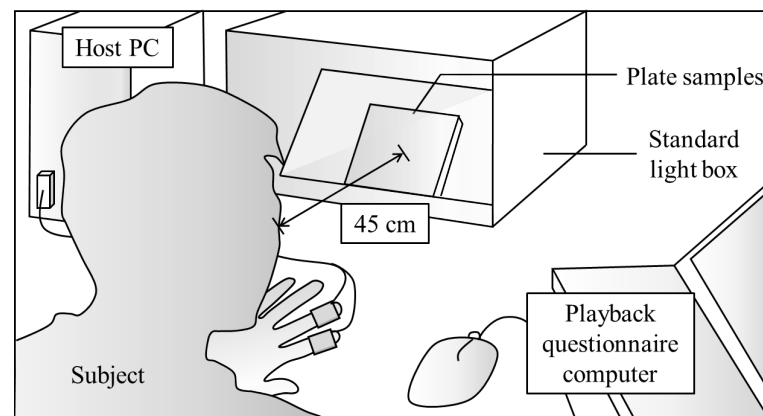


Figure 6. Laboratory environment diagram.

2.3. Participants

In this experiment, we recruited 20 students (10 males and 10 females) between 19 and 25 years of age. They were all from the School of Arts, had no prior exposure to experimental materials, and were unaware of this experiment's purpose. The participants in this study were a mix of master's and undergraduate students (6 master's students and 14 undergraduate students), all of whom had received art and design education for over 24 months. This educational background, coupled with their acute sense of observation, made them ideal for providing significant feedback on the data during the experiment. All participants had normal or corrected-to-normal vision, no tactile impairments or history of neurological disorders, and normal olfactory abilities. To ensure the accuracy of data collection, we required all participating students to abstain from alcohol and coffee and staying up late within 24 h before the experiment. We informed each participant of the experimental procedures and required them to sign a consent form.

2.4. Kansei Evaluation Items

In this study, we used the Semantic Differential method and the pair comparison method as the analysis methods for Kansei evaluation.

American scholars Osgood et al. [44] proposed the semantic differential (SD) method. It is a method that measures users' impression responses on a Likert scale and then analyzes the patterns, making it the cornerstone of effective evaluation research. On the one hand, it describes the impression style of the research object by finding impression words related to the research purpose. It uses pairs of opposite or contrasting adjectives, such as "beautiful-ugly", to measure the vague psychological concept of "impression" from different perspectives (or dimensions). It uses established 5-point, 7-point, or 9-point psychological scales to represent continuous psychological changes of different degrees using terms like very, entirely, somewhat, and uncertain (e.g., very beautiful, quite beautiful, somewhat beautiful, uncertain, somewhat ugly, quite ugly, very ugly). Due to the lack of research on impression evaluation related to tea waste material, we referred to the research case of Shen Dezheng et al. [24]. As part of our research process, we took the initiative to conduct a pre-experiment. This was done to collect impression evaluation items related to tea waste and create a semantic differential scale for our study. First, we used an open-ended questionnaire to collect adjectives related to tea waste material. The participants freely observed and recorded adjectives associated with the tea waste material samples from visual, tactile, and olfactory perspectives. A total of 40 students (18 males and 22 females between 19 and 25 years of age) were involved in the experiment, and the average experimental time was 15 min. We collected a total of 210 adjectives in this experiment. Then, we organized the collected adjectives by merging synonyms and sorting them according to their frequency of occurrence. Finally, we obtained 10 adjectives that appeared more than 13 times: hard, beautiful, environmentally friendly, expensive, civilized, comfortable, elegant, harmless, high-end, and modern. Therefore, this impression

evaluation experiment was based on these 10 adjectives. We used the Semantic Differential (SD) method for the specific method, where the adjectives were combined with their antonyms to form 7 segments of the SD scale (Figure 7).

Please answer what kind of impression the picture below would give you?
(Corresponding to different degree options, check the circle next to the corresponding score)
(Example only, content is different from the text)



	extreme	mild		mild	extreme	
Hard	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	Comfortable
Low-grade	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	High-grade
Ugly	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	Beautiful
Gaudy	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	Elegant
Cheap	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	Expensive
Backward	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	Modern
Crude	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	Civilized
Fragile	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	Strong
Harmful	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	Harmless
Polluting	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	Environmentally Friendly

Figure 7. The semantic differential scale used in the Kansei evaluation experiment.

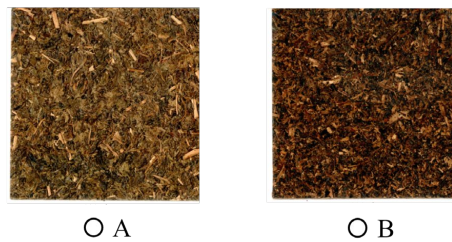
For our preference evaluation, we used Thurstone's paired comparison method to measure the participants' preferences for the experimental samples.

Fujii pointed out that in mathematical psychology, people express a preference as the ranking between choices [45]. Thus, preference refers to the relationship in which someone likes option B more than option A. In microeconomics, preference belongs to the category of consumer action theory. Consumers follow self-awareness and rank different consumption combinations based on the degree of their preference, which is the main factor affecting consumers' choice behavior. Therefore, studying preferences is necessary to explore consumers' choice behavior. Amartya Kumar Sen, the winner of the 1998 Nobel Prize in economics, described preference as "a binary relationship that internalizes choice" [46].

The paired comparison method proposed by Thurstone is not only a precise tool but also a practical one. It can effectively measure this kind of relationship. This method involves pairwise testing and evaluation of multiple experimental objects. In each pair, the one with a higher value is given a score of 1. The relative ranks of multiple experimental objects can be determined by adding up the results of each paired comparison and ranking them based on the total scores. This method is considered suitable for evaluating feelings and attitudes in psychological experiments, especially when it is necessary to simultaneously evaluate multiple experimental objects.

In this experiment, we used this method to evaluate people's preferences for experimental samples of tea waste. The experiment assistant required the participants to choose the preferred sample between two options based on their preference and input the selection result (Figure 8). After the selection, the experiment assistant provided a new sample combination, and the experiment ended when all combinations were completed.

When the following two samples are compared, which one would you choose? (Click on the circle below the image to select one)



“A” indicates a preference for the left,
“B” indicates a preference for the right

Figure 8. The paired comparison method used in the Kansei evaluation experiment.

2.5. Measurement of Users’ Emotions towards Materials

Changes in physiological signals often accompany emotional changes in humans. Compared to facial expressions or vocal signals, the advantage of physiological signals is that they can more accurately reflect the actual emotional state. In contrast, facial expressions and vocal signals are not subtle enough and can be easily masked [47]. Therefore, physiological signals are necessary input signals for emotion computation. In measuring users’ emotions regarding materials, researchers have found that heart rate signals and electrodermal activity (EDA) are essential sources of information for emotional states [48]. Heart rate variability (HRV) [49], can be derived from heart rate signals, reflecting changes in successive heartbeats. When subjects are stimulated, HRV is suppressed, while in a relaxed state, HRV returns to normal.

For example, changes in human emotions usually lead to physiological reactions in the skin. The skin is the organ that has the closest contact with the external environment, and research has shown that EDA is beneficial for emotion recognition [50]. Electrodermal activity is one of the most sensitive emotional feedback signals, originating from the autonomous activation of the sweat glands in the skin. It is closely related to emotions, arousal, and attention and is the most widely used measurement indicator type in the physiological response system. Due to its high stability, ease of measurement, and high sensitivity, it has become the most effective and sensitive physiological parameter for reflecting changes in sympathetic nervous system excitability. Electrodermal activity is an excellent indicator in evaluating individual physiological arousal, cognitive load, effort level, emotional response, and stress resilience.

In terms of physiological signal parameters, studies have shown that time-domain indicators of HRV, such as heart rate (HR) and skin conductance level (SCL) in EDA, are related to emotions [51–53]. HR refers to the number of heartbeats per minute in an average individual at rest, measured in beats per minute (bpm). Time-domain indicators mainly reflect the tension of the sympathetic and parasympathetic nervous systems and thus evaluate the overall level of the autonomic nervous system. An increase in the average heart rate often indicates an increase in the subject’s emotional arousal. SCL is the most commonly used indicator in electrodermal activity, which measures the skin’s ability to conduct electricity by applying a small constant voltage between two points on the skin. Since the nervous system regulates electrodermal activity, SCL is linearly correlated with the level of arousal. The trend of SCL changes can reflect emotional experiences over time (e.g., happy and sad emotions can trigger higher skin conductance levels). Researchers often use SCL to study mental load and emotional states in human–computer interactions. For example, when users play computer games, their SCL reactions peak quickly from almost scoring a goal to scoring a goal, indicating a high level of emotional excitement [54].

Regarding the measurement equipment for this experiment, the experiment uses ErgoLAB Human-Machine-Environment Synchronization Platform V3.0 (Beijing, China)

from Kingfar International Inc. It can simultaneously record subjective scale ratings and questionnaire and behavioral experiment paradigm results. The platform also includes analysis modules for heart rate variability (HRV), electroencephalogram (EEG), electrodermal activity (EDA), electromyogram (EMG), behavior coding, motion capture, eye tracking, and spatial-temporal behaviors, as well as interaction behavior and sequence analysis. Meanwhile, it enables custom editing and design under various research conditions, including laboratory, virtual reality, mobile device-based testing, and real-world environments.

The current experiment used the design module of ErgoLAB 3.0, EDA, PPG sensors from the wearable physiological recording system (Kingfar International Inc. Beijing, China), and the HRV analysis module (Kingfar International Inc.). Data were processed with ErgoLAB 3.0 data analysis modules, and statistical tests were done with SPSS.

2.6. Experimental Process

Prior to the start of the experiment, the experiment assistant guided participants to sit in the experimental position. The experiment assistant explained the experimental procedure to the participants for about 2 min. Once the experiment assistant determined that the participants understood the content and procedure of the experiment, the physiological measurement devices were worn by the participants. After properly adjusting the physiological measurement devices, the experiment assistant asked the participants to close their eyes and rest for 2 min. We used participants' rest to prevent excessive nervousness or excitement that may lead to abnormal baseline physiological data. The overall experimental procedure is shown in Figure 9.

The experiment assistant placed the experimental samples inside the light source box. We asked the participants to observe the samples from 45 cm for 10 s. Then, the participants touched the surface of the samples from left to right using their index and middle fingers for 10 s. The direction of the left-to-right touch was consistent with the direction we used to test the surface texture of the samples with a surface texture analyzer. Finally, the participants smelled the samples with their noses for 10 s. After the 30 s sample observation, the experiment assistant presented a new sample and repeated the above actions. Once the participants had tested all six samples, the experiment assistant stopped measuring physiological data. Afterward, we asked the participants to move to another computer to complete the subjective questionnaires. We used the SD and Thurstone's paired comparison scales to measure the participants' impressions and preferences for the experimental samples. After the questionnaires were completed, the experiment ended. The entire experiment lasted approximately 11 min.

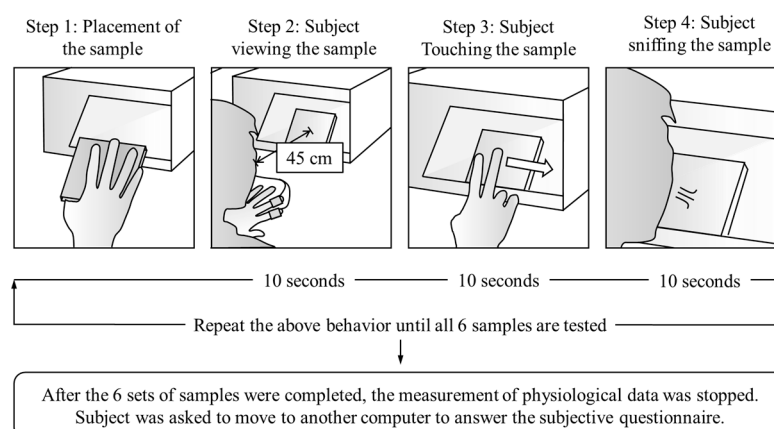


Figure 9. Experimental flow chart.

2.7. Data Analysis

After the completion of this experiment, we obtained three sets of different data:

- The physical qualities of the tea waste material experimental samples (color, surface texture, and odor);
- The Kansei data from the participants (impressions and preferences);
- The physiological data (HR and SCL). We mainly extract the average HR (in bpm) and SCL (in μ S) values of each of the 20 participants under each of the six materials, as well as the baseline HR and SCL values during a 2 min resting state, and subtract the original data from the baseline data to obtain the final data values. These values may help determine the participants' emotional arousal levels to the materials.

To extract the physical qualities that can enhance the Kansei value, we used the Statistical Package for the Social Sciences (SPSS) for data analysis. First, we used factor analysis to reduce the dimensions of the impression evaluation items and explore the underlying factors. Then, based on the scores of each tea waste material experimental sample, we generated factor distribution maps to subjectively analyze the participants' impression evaluation states for each sample. Subsequently, we embarked on a crucial correlation analysis of the physical qualities of the samples and the participants' affective and physiological data. This analysis unveiled the intricate relationships among these factors, leading to intriguing insights.

3. Experimental Results and Discussion

3.1. Factor Analysis Results

We conducted a factor analysis on the semantic differential scale data. Using factor analysis, we successfully reduced the original ten sets of adjectives into two factors (Table 2), with a cumulative contribution rate of 86.963%. The first factor included eight adjectives: hard—comfortable, low-grade—high-grade, ugly—beautiful, gaudy—elegant, cheap—expensive, backward—modern, crude—civilized, and fragile—strong. The eigenvalue of this factor is 6.305, accounting for a cumulative contribution rate of 63.046%. The adjectives included in the first factor were mainly related to the participants' sensory experiences, so we named it the sensory factor.

The second factor included two adjectives: harmful—harmless and polluting—environmentally friendly. Its eigenvalue is 2.392, accounting for a cumulative contribution rate of 23.918%. The adjectives included in the second factor were related to safety, so we named it the safety factor.

Table 2. Factor analysis results.

Item	Factor 1	Factor 2
Hard–Comfortable	0.955	
Low-grade–High-grade	0.952	
Ugly–Beautiful	0.936	
Gaudy–Elegant	0.894	
Cheap–Expensive	0.874	
Backward–Modern	0.859	
Crude–Civilized	0.813	
Fragile–Strong	0.770	
Harmful–Harmless		0.980
Polluting–Environmentally Friendly		0.927
Eigenvalue	6.305	2.392
Contribution rate	63.046%	23.918%
Cumulative contribution rate	63.046%	86.963%

Figure 10 shows the factor distribution map generated based on each sample's factor scores. The graph shows that Sample 4 has the highest scores in both the sensory and safety factors. On the other hand, Sample 6 has the lowest score in the sensory factor, while Sample 5 has the lowest score in the safety factor. Based on these results and each sample's material sources and physical compositions, we can draw the following subjective analysis results. Firstly, Sample 1 and Sample 4 come from the same type of tea waste material

(oolong tea stems). During the processing, larger fibers were compressed to form the upper surface of Sample 1, while relatively more minor fibers and powder settled to form the lower surface of Sample 4. Therefore, Sample 4 appears to have a finer texture visually, but there is no significant difference between the two in terms of their friction coefficient, frictional variation, and surface roughness. The main differences lie in the visual and olfactory aspects. Regarding the L^*C^*h values that reflect visual performance, L stands for the material's lightness, C for chroma, and h for hue. Sample 4 and Sample 1 have significant differences in brightness and chroma, making Sample 4 visually brighter and more vibrant in color. Moreover, Sample 4 has a more noticeable scent compared to Sample 1.

The main reason for the low score in the sensory factor for Sample 6 is its low brightness and color purity (the L and C values of Sample 6 are the lowest among all samples) and its excessively rough surface (the highest SMD among all samples). Sample 6 differs from the other samples because its raw material comes from tea residues discharged after processing in a tea beverage factory. Although it has a strong aroma, the roughness and impression of being less durable associated with tea residues reduced the participants' evaluations of the sensory factor.

Sample 5, which originates from fully fermented black tea stems, is dark red with low brightness and a tendency toward deeper colors, which is the main reason for its low score in the safety factor.

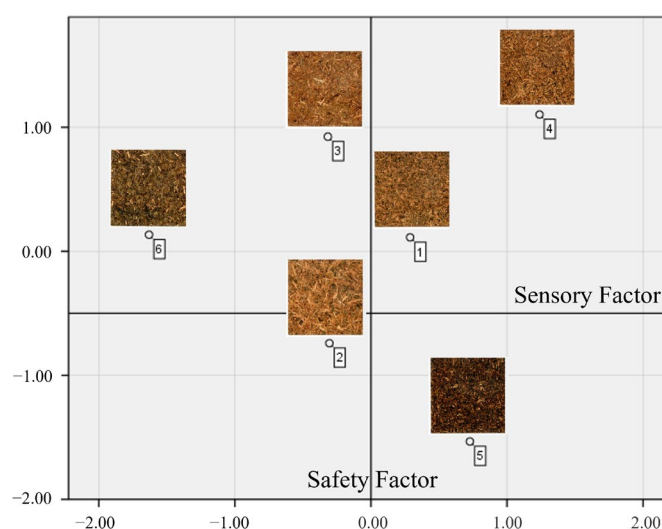


Figure 10. Factor distribution chart.

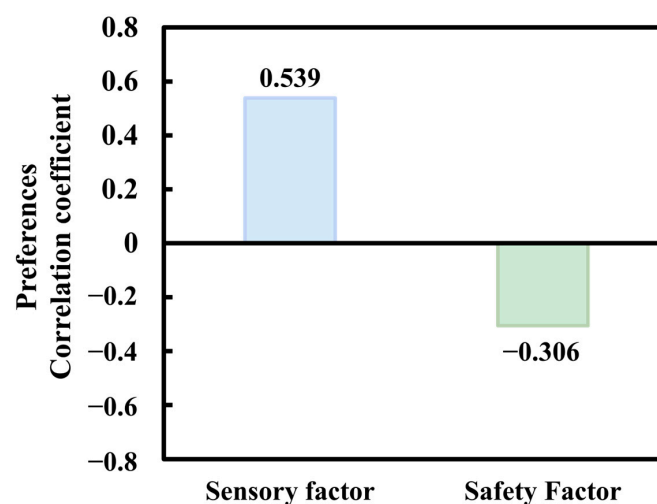
3.2. Correlation Analysis Results Comparing Samples' Physical Qualities and Kansei Data

Before conducting the correlation analysis, we checked the normal distribution of the physical qualities and the Kansei data from the participants to determine the appropriate correlation analysis method. Due to the small sample size of this experiment, we relied on the results of the Shapiro–Wilk test for normality testing. Table 3 shows the specific test results, including the Shapiro–Wilk Test Statistic (Statistic), the degrees of freedom (df), and the two-tailed significance or p -value (Sig.). When the p -value of the test result is less than 0.05, the data are considered to be non-normally distributed. The table shows that except for the odor concentration index and MMD, all other parameters conform to a normal distribution. Therefore, we used the Pearson correlation coefficient for the parameters that follow a normal distribution. We used the Spearman correlation coefficient to analyze the odor concentration index and frictional variation, which do not follow a normal distribution.

Table 3. Analysis of normal distribution test results of physical qualities and Kansei data.

	Statistic	Shapiro–Wilk df	Sig.
Odor concentration index	0.776	6	0.036
MIU	0.934	6	0.613
MMD	0.767	6	0.029
SMD	0.909	6	0.430
L value	0.845	6	0.142
C value	0.949	6	0.732
h value	0.870	6	0.227
Sensory factor	0.960	6	0.818
Safety factor	0.937	6	0.632
Preferences	0.929	6	0.572

The analysis results showing the Pearson correlation coefficient when comparing impressions and preferences are shown in Figure 11. Preferences exhibit distinct relationships with the two factors. Specifically, preferences show a positive correlation with the sensory factor (Pearson coefficient of 0.539), indicating that higher scores in the sensory factor are associated with greater favorability from the participants. There is a negative correlation between safety factors and preferences (Pearson coefficient of -0.306), but it is insignificant.

**Figure 11.** The results of correlation analysis between impression and preference.

In the previous section, we analyzed the relationship between impression and preference, and in the results, we learned that there is a positive correlation between sensory factors and preference. Here, we analyze the relationship between the sensory factors and the physical qualities of the samples. According to the correlation analysis results in Figure 12, the MIU, SMD, and hue value have a negative correlation with sensory factors, and SMD has a significant negative correlation ($p < 0.01$). A relatively rough surface will lower the evaluation of sensory factors, while a smooth texture may result in a better impression of the material for participants. In addition, the L and c values of the material are positively correlated with sensory factors but not significantly. The odor concentration index and MMD were analyzed using the Spearman correlation coefficient, and both showed a negative correlation with sensory factors, but they were not significant.

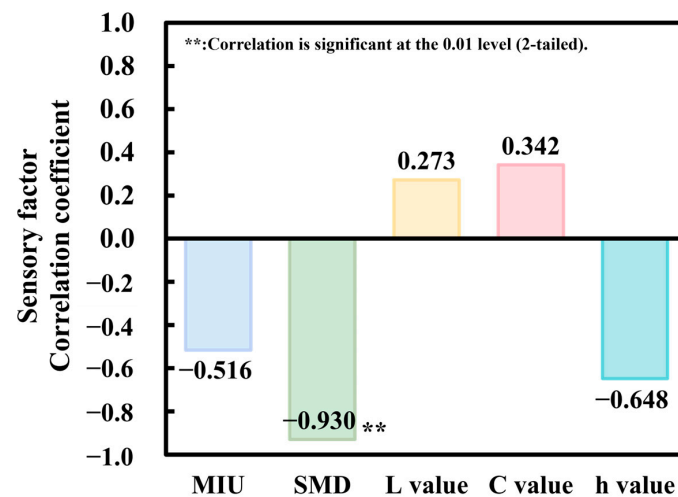


Figure 12. Correlation analysis results comparing sensory factors and physical qualities.

Figure 13 represents the correlation between the safety factors and the physical qualities of the samples. The table shows a positive correlation between the material's MIU and safety factors. In addition, the material's L value (brightness) also has a specific positive correlation, but none of the values are significant. Furthermore, the odor concentration index and the MMD show a positive correlation with safety factors, especially the odor concentration index, which has a higher correlation.

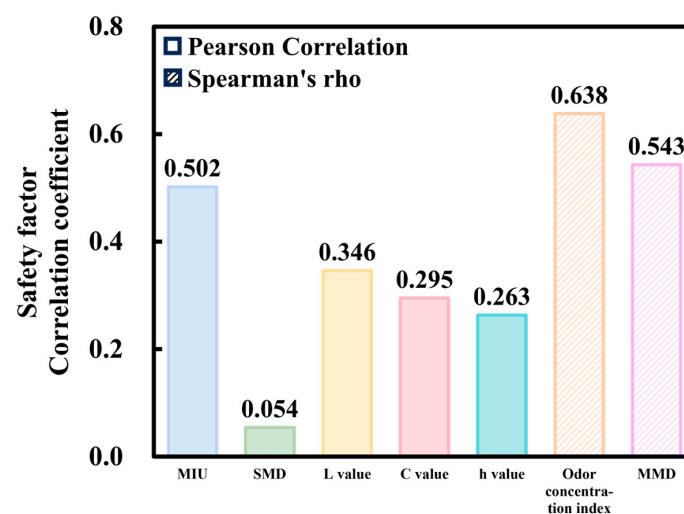


Figure 13. Correlation analysis results comparing safety factors and physical qualities.

3.3. Correlation Analysis Results Comparing Samples' Physical Qualities and Physiological Data (Emotion)

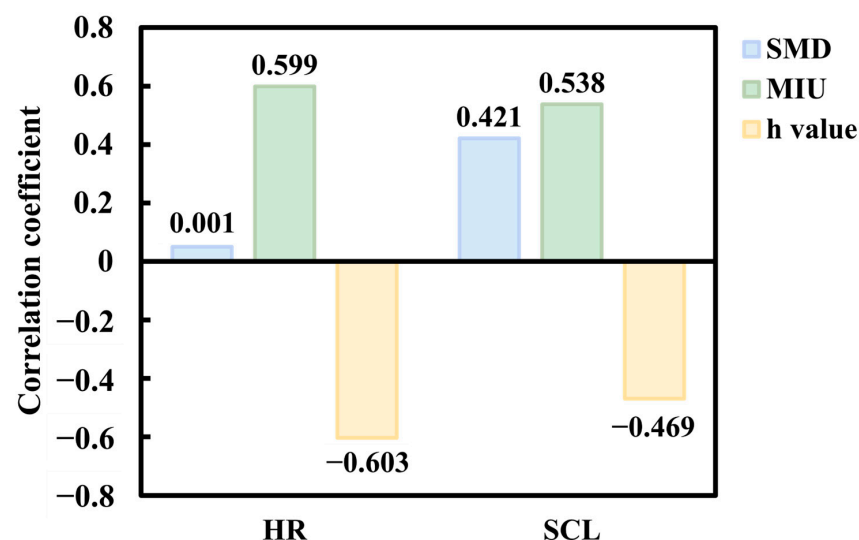
In the previous section, we analyzed the relationship between the physical qualities of the samples and participants' Kansei data. We found a significant negative correlation between the surface roughness of the samples and sensory factors. Additionally, surface roughness and the hue value representing color (h value) also have a strong negative correlation with sensory factors. The odor index of the samples shows a strong positive correlation with safety factors. Here, we further analyze this physical quality of emotions from the perspective of physiological data. First, we analyzed whether the physiological data followed a normal distribution. According to the expected distribution results in Table 4, all the measured data in this experiment follow a normal distribution. Therefore, we only used the Pearson correlation coefficient for the correlation analysis.

Table 4. Normal distribution test results of physiological indicators.

	Statistic	Shapiro–Wilk df	Sig.
HR	0.987	6	0.981
SCL	0.847	6	0.148

The correlation between SMD and physiological data, which strongly correlate with sensory factors, is shown in Figure 14. We can observe that SMD strongly correlates positively with SCL. This result indicates that when the material's surface becomes rough, it increases the participants' cognitive load and stress. This same reaction is also reflected in the friction coefficient of the material. The friction coefficient describes the resistance generated when the fingers come into contact with the surface of the experimental sample and rub against each other, which can directly reflect the participants' tactile experience of the sample. The figure shows that HR and SCL have a strong positive correlation with the friction coefficient. This result further confirms that a material's rough surface leads to increased friction, which increases participants' psychological burden and cognitive pressure, thereby negatively affecting the scores of sensory factors. Li Wei validated the results of this experiment in a study. They found that physiological indicators, especially electroencephalogram (EEG), are enhanced with increasing surface friction of the materials [55].

The h value represents the color angle and indicates the color tone, ranging from 0 to 360. In this range, 0 represents red, 180 represents green, and 360 represents blue. The results in the table show a robust negative correlation between the hue value and HR and SCL. This result indicates that as the hue value increases, the participants' psychological burden and cognitive pressure decrease. Currently, the hue values of the samples range from 60 to 70, predominantly in the red color range. Based on the data, we speculate that when the sample color changes to green or blue, participants may experience more positive emotions. Research on wood color tone has proven to influence psychological preference significantly. A high h value makes it easier to gain more visual attention [56].

**Figure 14.** Correlation analysis results of physical qualities and physiological indicators related to sensory factors.

Due to the abnormal distribution of the odor concentration index, which strongly correlates with safety factors, we used the Spearman coefficient for correlation analysis. Figure 15 shows that the odor concentration index has a strong positive correlation with HR and SCL. This result indicates that as the odor of the material becomes robust, it increases the participants' cognitive load and stress. At the same time, an increase in the odor

concentration also affects an increase in safety factor scores. Since safety factors negatively correlate with user preference, an increase in safety factor scores may lead to a decrease in participants' preferences. It is important to note that the odor concentration index here represents only the intensity of the odor and does not involve the specific odor types. In the evaluation of engineered wood materials, materials with strong odors often indicate the excessive use of adhesives and may have high formaldehyde emissions, which often cause concern and anxiety, especially in the laminate furniture market. People tend to avoid such furniture due to concerns about the potential impact of formaldehyde on their health.

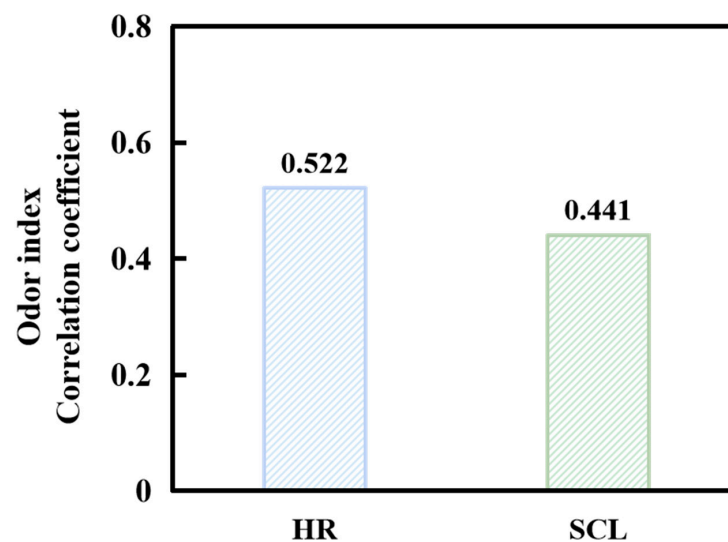


Figure 15. Correlation analysis results of physical quality and physiological indicators related to safety factors.

4. Conclusions

In the introduction of this study, we first mentioned the issues existing in the current research on Kansei evaluation, which, despite being crucial in enhancing products' added value, could be improved in several aspects. For example, the concepts of impression and preference, despite frequently appearing in research, have inherent differences and different evaluation methods. Furthermore, due to the different definitions of preference in everyday language and research terminology, preference and impression often need clarification. Both impression and preference are indispensable in practical design applications, but no research method can simultaneously enhance both aspects. Based on these issues, we have proposed a research model that integrates impression and preference by combining commonly used models. This model quantifies the experimental subjects' physical qualities, impressions, and preferences using corresponding measurement methods. Then, it analyzes the quantitative relationships between these factors to extract design principles that enhance impression and preference simultaneously. Additionally, we recognize the importance of emotions in material evaluation. Therefore, another innovative aspect of this model is incorporating physiological indicators that can reflect emotions into the evaluation model, assisting in explaining the impact of materials' physical qualities on participants.

In this experiment, we discovered that the physical qualities of sustainable materials, such as tea waste, simultaneously affect participants' sensory perceptions and emotions. Specifically, we found that the material's SMD affects people's evaluation of sensory factors and subsequently reduces preference. Physiological data further support this finding, as increased surface roughness leads to increased cognitive load and psychological stress, resulting in negative emotions. The material's MIU, hue, and odor concentration index also impact users' psychological and physiological responses.

Kansei value is a crucial way to increase added value. In this study, our proposed approach to Kansei-driven materials has important implications for enhancing their Kansei

value. For example, we can optimize the surface texture of materials and reduce their roughness to improve customers' sensory evaluation. At the same time, we must pay attention to the relationship between odor concentration and safety, minimizing the creation of impressions of a product being harmful to one's health due to strong odors. Compared to previous studies, our proposed method extracts parameters that can quantitatively affect people's Kansei value. By changing these parameters, we can enhance the Kansei value and thereby increase the added value of the materials.

It is important to note that these analysis results, while based on observations and analyses of the current sample, have significant practical implications. However, further research and validation are needed to determine their universality and generalizability. This experiment's shortcoming is the small number of participants, which is due to limitations in the experimental conditions. Furthermore, we needed to be more rigorous in sample size selection. With these preliminary findings, we aim to provide valuable insights and guidance for future material design and development. In future research, we will seek to improve and refine our study in the following ways: apply the method proposed in this study to wooden materials to explore the differences in Kansei value between expensive solid wood materials and inexpensive artificial board materials; introduce the variable of material form to investigate the impact of materials in different forms on people's Kansei value; and increase the number of experimental participants and the population's diversity to further enhance the practical application potential of this research.

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