

Preparation of Recycled Paper Using Tea Stems and its Application in Product Design

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Abstract: (1) Objective: This study aims to reduce waste and resource usage by utilizing discarded tea stems for producing recycled paper, and to explore its properties and potential in product design. (2) Methods: Tea stem recycled paper was fabricated via a conventional hand-sheet process using varying tea stem-to-pulp ratios, followed by physical property testing and Kansei-based visual-tactile evaluations. (3) Key Findings: Tea stem recycled paper showed comparable whiteness, moisture content, and opacity to commercial recycled papers, with the highest tensile strength at 10% tea stem content ($12.3 \pm 0.4\%$ higher than Xuan paper). (4) Implications: Based on combined physical and sensory assessments, material-driven design models were proposed, highlighting functional uses for tea stem-pulp composites and aesthetic applications for tea stem-bark composites.

Keywords: Kansei engineering; material driven design; paper design; sustainable design; tea waste

1 INTRODUCTION

Tea originated in China and is widely considered the "national drink" [1]. Tea drinks are rich in organic chemical compounds and inorganic minerals. It is a natural, healthy drink and is one of the top three most popular drinks in the world. China has a long tradition of tea consumption and has developed a distinctive cultural phenomenon around this custom that appeals to a large domestic consumer audience [2].

According to the China Industrial Research Institute, China's tea production increased from 2.3133 million tons in 2016 to 3.3421 million tons in 2022. Nevertheless, the tea growing, harvesting, processing and consumption processes generate a significant amount of waste. Tea waste consists mainly of leaf residues and tea stems. Typically, leaf residue is treated as combustible waste, while tea stems are burned or buried. As mechanical vegetable harvesting becomes more common, the amount of discarded tea stems is increasing. Current research suggests that discarded tea stems account for 20-30% of total tea production [3, 4].

Burning discarded tea stems not only causes environmental pollution but also results in economic losses for tea production companies. In this study, recycled paper is produced from tea stems and experimental evaluations of the physical properties and sensory properties of the recycled paper are carried out. The aim is to investigate the use of tea stems as recycled paper in product design and to offer innovative concepts for recycling and reusing tea stems.

2 RESEARCH OBJECTIVES AND PROCESS

2.1 Research Objectives

As part of the waste generated during tea processing, this study initially aims to convert tea stems into recycled paper. This reduces disposal of tea stems and minimizes resource waste, ultimately increasing resource efficiency.

Second, studying the use of tea stems as a raw material for the production of recycled paper can promote technological innovation in the pulp and paper industry. Tea stems contain a variety of valuable components, including tea polyphenols, organic acids, cellulose and more. As a result, the paper produced offers numerous

advantages. In addition, the use of tea stalks in paper production will reduce the dependence on traditional pulp, resulting in conservation of the environment and reduced environmental impact.

Third, tea stems are an integral part of tea culture, and the recycled paper obtained from it has considerable artistic value. From a design perspective, creating high-quality products from tea waste is a central element in the study of tea culture. In addition, this promotes the development of new business prospects and stimulates economic growth.

2.2 Research Methods and Process

This study uses the Material Driven Design (MDD) research method proposed by researcher Eleven Elvin Karana from Delft University of Technology in the Netherlands for the development and application of new materials [5]. The MDD method emphasizes that the development of new materials should not be limited to the physical properties of the materials themselves; Studying material experience is also a crucial step. The specific research process is shown in Fig. 1.

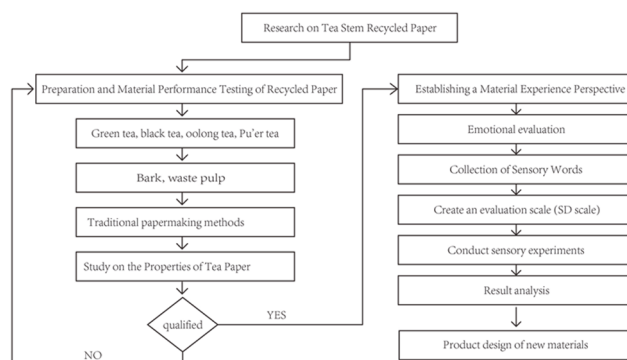


Figure 1 Flowchart of the experiment

First, recycled paper is made using the papermaking method from tea stems and waste pulp of green tea, black tea, oolong tea and pu-erh tea, as well as bark of the paper mulberry tree. Then, their physical properties are tested and samples with good performance are selected for visual and tactile impression experiments. Based on the results of both the physical properties and sensory experience of the

material, a design model for the materials is created and design proposals are presented based on this model.

3 MATERIAL EXPERIMENTS

3.1 Material and Experimental Equipment

3.1.1 Tea Stems

Four types of tea stems were used as the primary fibrous material: green tea, black tea, oolong tea, and pu-erh tea stems. These stems are the woody residual twigs of the *Camellia sinensis* plant remaining after tea leaves are processed. Each tea type undergoes a different production process, which may impart distinct characteristics to the fibers. Using a range of tea stem types allowed us to investigate whether tea variety influences the properties of the recycled paper. The collected tea stems were dried and then mechanically pulverized into pulpable fiber slurry for papermaking.

3.1.2 Auxiliary Material Selection

In addition to tea stems, several auxiliary materials were incorporated to facilitate papermaking and enhance paper quality. Paper mulberry bark was chosen as a supplementary fiber source, as it is a traditional papermaking material known for producing strong, high-quality paper. We also used waste paper pulp, composed mainly of recycled cellulose fibers, to represent a recycled paper component and improve fiber bonding. A plant-based papermaking glue (binder) was added as well; this natural adhesive, containing ingredients such as aloe and cactus extracts mixed in water, helps bind the fibers together during sheet formation.

3.1.3 Experimental Equipment

The following equipment was used during the material preparation and papermaking process: a thermostatic water bath (Model HH-600) for soaking and heating the pulp mixtures, a precision electronic balance for measuring material ratios, a traditional stone mill and wooden hammer for initial pulping of tea stems, glassware (measuring cups and stirring rods) for preparing and mixing additives, a papermaking mesh screen for forming wet sheets, a laboratory pulp beater for refining fibers, and an electric hot-air drying oven (Model XMTA-500T) for drying the paper sheets.

3.2 Manufacturing Process of Tea Stem Recycled Paper

The tea stem recycled paper was produced using a conventional hand-sheet papermaking process, as illustrated in Fig. 2. In this process, the prepared pulp (containing tea stem fibers, auxiliary fibers, water, and binder) was diluted to a suitable consistency and then poured onto a mesh screen. Initial dewatering on the screen allowed a wet fiber mat to form. This wet sheet was then pressed to remove excess water and dried in the hot-air oven to produce the finished paper. Key steps included uniformly distributing fibers in water, removing water through gravity and gentle pressing, and carefully drying the sheet to avoid warping. This method was used to create all experimental paper samples for subsequent testing.

In this study, the pulp consistency during sheet formation was maintained at 2.5%, beating/refining time was set to 40 minutes, pressing pressure was approximately 350 kPa for 5 minutes, and drying was conducted at 105 °C for 20 minutes to ensure reproducibility.

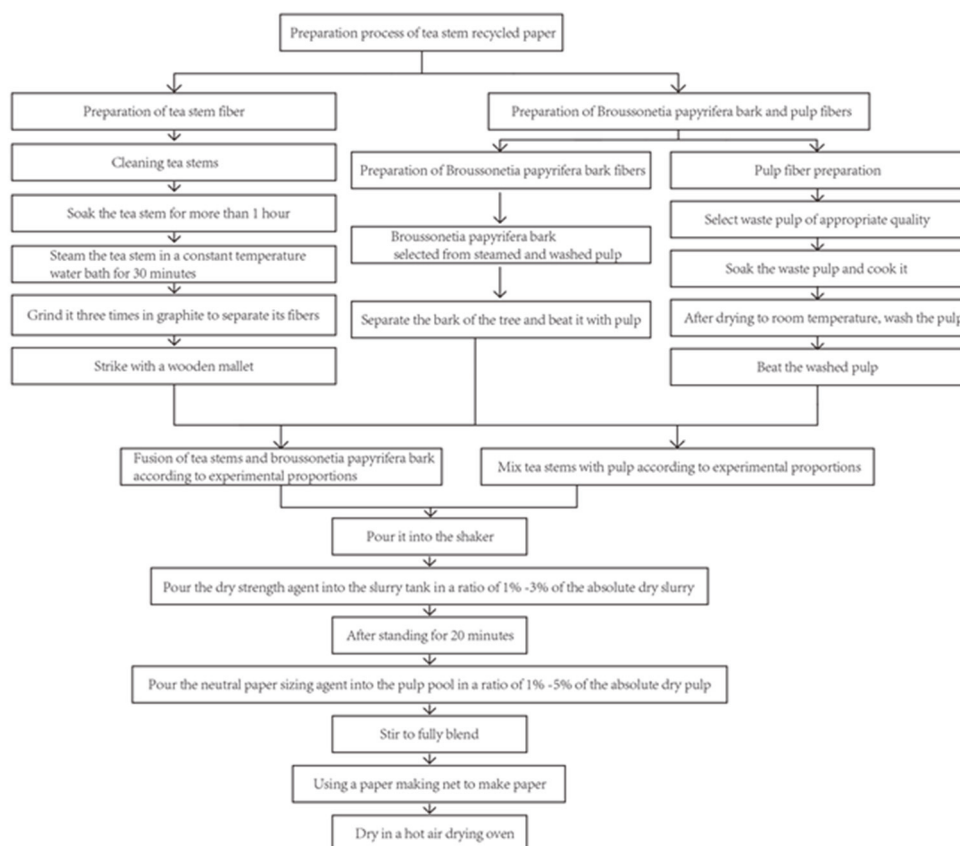


Figure 2 Flowchart for making experimental samples

3.3 Experimental Sample

During the experimental process, it was found that the maximum addition of tea stems in recycled paper is 70%. If this value is exceeded, the recycled paper becomes unformable. To better investigate the relationship between tea stem proportions and recycled paper, as shown in Figure 3, in this experiment, samples were processed with tea stem additives of 10%, 30%, 50%, and 70% using waste pulp and paper-mulberry bark composites. Fig. 4 represents 34 example varieties.

Sample number	Tea Stems	Grams of tea stem (g)	Grams of waste paper pulp (g)	Sample number	Tea Stems	Grams of tea stem (g)	Grams of tree bark (g)
1	Nothing	0	100	18	Nothing	0	100
2	Green tea stems	10	90	19	Green tea stems	10	90
3	Green tea stems	30	70	20	Green tea stems	30	70
4	Green tea stems	50	50	21	Green tea stems	50	50
5	Green tea stems	70	30	22	Green tea stems	70	30
6	Black tea stems	10	90	23	Black tea stems	10	90
7	Black tea stems	30	70	24	Black tea stems	30	70
8	Black tea stems	50	50	25	Black tea stems	50	50
9	Black tea stems	70	30	26	Black tea stems	70	30
10	Pu-erh tea stems	10	90	27	Pu-erh tea stems	10	90
11	Pu-erh tea stems	30	70	28	Pu-erh tea stems	30	70
12	Pu-erh tea stems	50	50	29	Pu-erh tea stems	50	50
13	Pu-erh tea stems	70	30	30	Pu-erh tea stems	70	30
14	Oolong tea stems	10	90	31	Oolong tea stems	10	90
15	Oolong tea stems	30	70	32	Oolong tea stems	30	70
16	Oolong tea stems	50	50	33	Oolong tea stems	50	50
17	Oolong tea stems	70	30	34	Oolong tea stems	70	30

Figure 3 Material addition ratio: (a) Tea stems and waste paper pulp; (b) Tea stems and tree bark



Figure 4 Schematic of the samples

4 PHYSICAL PROPERTIES OF TEA STEM RECYCLED PAPER

In order to better study the physical properties of tea stem recycled paper, we will prepare the above samples according to GB/T 451.2 standard for basis weight, GB/T 462 standard for moisture content, GB/T 8940.1 standard for measuring the whiteness and the GB/T 8940.1 standard for whiteness. T 1543-2005 standard for opacity and GB/T 12914-2018 standard for tensile strength. To better understand the performance characteristics of tea stem recycled paper, we conducted a comparative study of the physical properties of the most commonly used recycled papers. The selected recycled papers include Xuan paper, hemp paper and mulberry bark paper. Xuan paper stands out among recycled papers and is widely used in various fields such as printing, painting mounting and gift wrapping for crafts [7]. Hemp paper is a sturdy paper made primarily from materials such as flax, cloth and leather. Mulberry bark paper, on the other hand, is recycled paper made from materials such as wild mulberry bark, carambola flowers and basswood. Hemp paper and

mulberry bark paper are commonly used for envelopes and various products such as umbrellas, baskets and Chinese fan [8].

4.1 Basis Weight

The basis weight of paper indicates the quality and density of the paper. A higher basis weight typically indicates thicker paper suitable for applications requiring more structural support, while a lower basis weight typically indicates thinner paper suitable for writing, printing and packaging applications. Different surface weights are suitable for different product requirements. As shown in Fig. 5, mulberry paper has the highest basis weight at 100 g/m², while mulberry bark paper has the lowest basis weight at only 35 g/m². Recycled paper made from tea stems has a higher basis weight than Xuan paper, but lower than mulberry paper.

The basis weight of recycled paper made from waste tea stem pulp is slightly higher than that of recycled tea stem bark paper. Among the four types of tea stems, the highest basis weight was achieved with black tea stems as raw material, reaching 92.34 g/m² at an addition rate of 70% for recycled paper made from black tea stem waste pulp and 79.4 g/m² for recycled paper made from black tea stem bark. The lowest basis weight was observed for green tea stems as raw material, with only 69.1 g/m² at an addition rate of 70% for recycled paper from green tea stem waste pulp and 57.36 g/m² for green tea stem bark. Recycled paper. The results of the basis weight measurements show that the greater the proportion of tea stems, the greater the basis weight of recycled paper. Different tea stems and composite materials result in different basis weights.

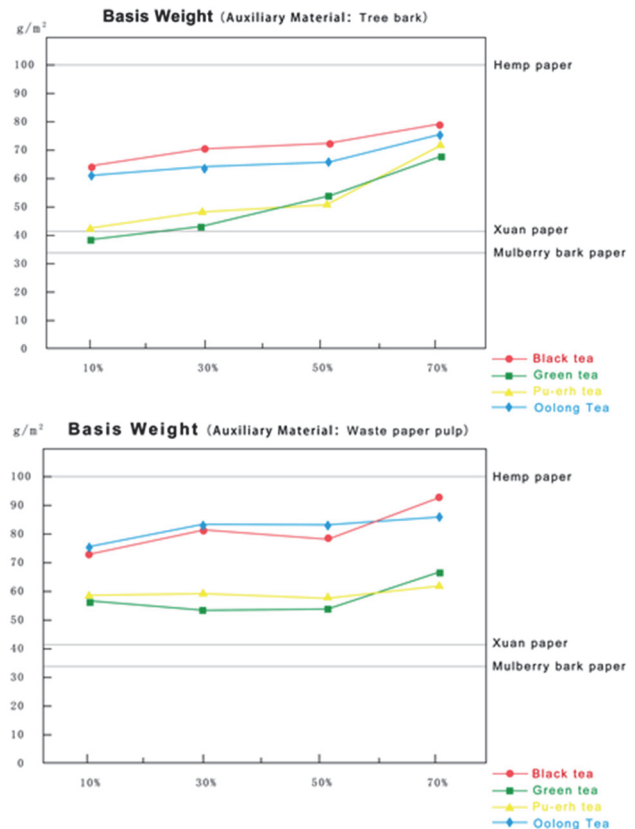


Figure 5 Basis weight of samples

4.2 Whiteness

The whiteness of paper refers to its ability to reflect light on the surface and is usually used to measure the whiteness or brightness of the paper. The higher the whiteness of the paper, the whiter the surface of the paper and the more light it reflects. As shown in Fig. 6, the whiteness of recycled paper made from tea stems, waste paper pulp and bark composite decreases with increasing tea stem content. There is no significant difference in whiteness between recycled paper made from tea stems, recycled paper pulp and bark composite. In addition, the whiteness of recycled tea stem paper is lower than that of Xuan paper, hemp paper and mulberry bark paper.

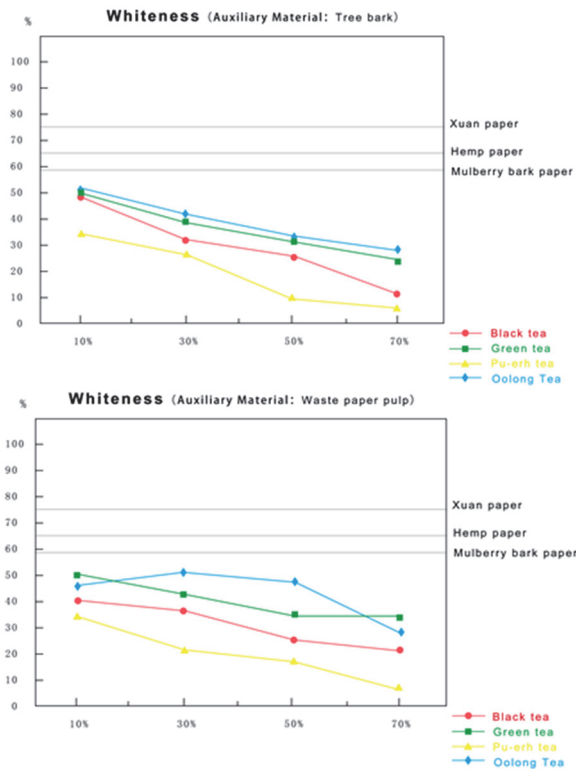


Figure 6 Whiteness of samples

4.3 Opacity

The opacity of paper refers to its ability to block the passage of light, and opacity is an important indicator of paper quality, particularly in printing and publishing. High opacity paper ensures that light does not penetrate during printing, improving print quality and preventing show-through.

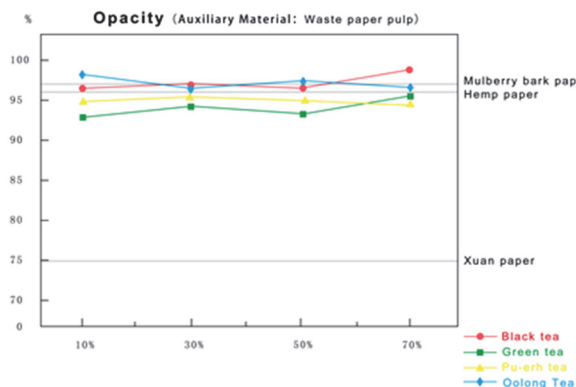


Figure 7 Opacity of samples

As shown in Fig. 7, the opacity of recycled paper made from tea stems, waste paper pulp and bark composite decreases with increasing tea stem content.

There is no significant difference in opacity between recycled paper made from tea stems, recycled paper pulp and bark composite. The opacity of the samples is all higher than that of Xuan paper, and is similar to the opacity of hemp paper and mulberry bark paper, which is all above 95%.

4.4 Moisture Content

Moisture content refers to the water content in the paper and indicates the water content in relation to the dry weight of the paper. Moisture content can affect the quality and performance of paper. As shown in Figure 8, with an increase in tea stem content, there are no significant fluctuations in moisture content for recycled paper made from tea stems, waste paper pulp and bark composite. The moisture content of tea stem recycled paper is slightly lower than that of Xuan paper and is at a similar moisture level to hemp paper and mulberry bark paper.

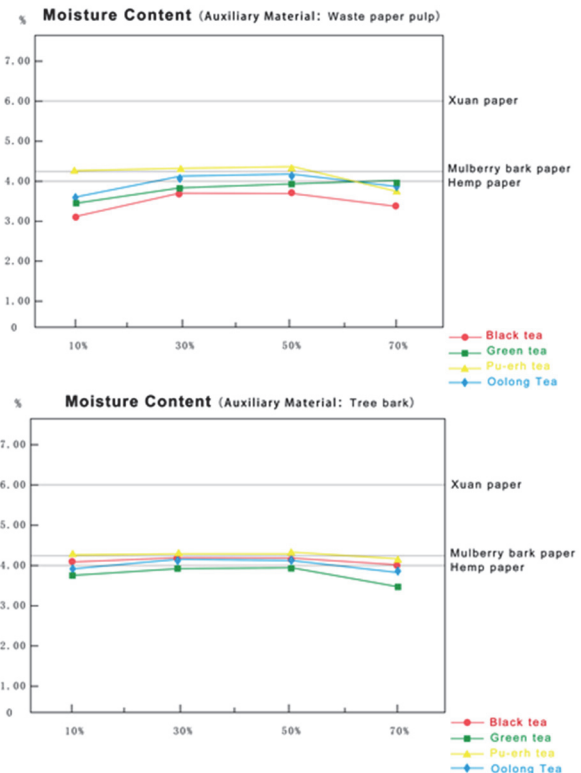


Figure 8 Moisture content of samples

4.5 Tensile Strength

Tensile strength refers to the ability of paper to withstand stretching forces. Tensile strength is a crucial indicator describing paper quality and influences its performance in various applications. Strong tensile properties provide more choices for paper in future product processing. As shown in Fig. 9, at 10% tea stem content, the tensile strength of recycled tea stem-waste paper pulp is superior to that of recycled tea stem-bark composite paper. However, with a tea stem content of 70%, there is only a small difference in tensile strength between tea stem recycled paper pulp and recycled tea stem bark composite paper. In addition, the tensile strength of recycled paper decreases as the proportion of tea stems increases. Among the four tea stem materials, black tea stem recycled paper has the best tensile strength. When the content is less than 50%, the tensile strength is higher than Xuan paper. In contrast, recycled paper made from green tea stems has the worst tensile strength, except for the 10% portion combined with waste paper pulp, all other tensile strengths are worse than Xuan paper.

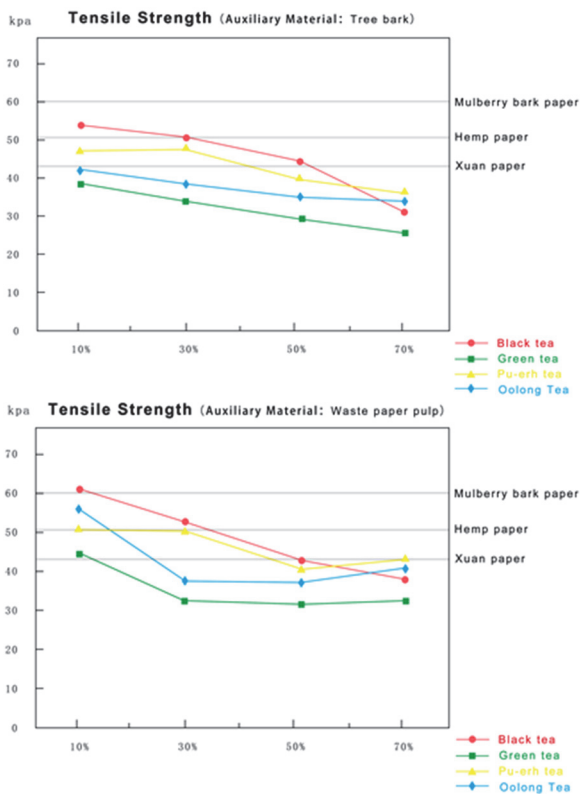


Figure 9 Tensile strength of samples

4.6 Summary of Physical Properties

Based on the above experimental results, we can summarize the effects of incorporating tea stem fibers on paper properties as follows. Within the tested range (10-70% content), adding tea stems did not drastically degrade the fundamental qualities of the paper. The tea stem recycled papers remained comparable to ordinary Xuan paper, hemp paper, and mulberry bark paper in terms of basis weight, opacity, and moisture content. In these aspects, the tea stem content showed little to no significant impact - for instance, even at high tea fiber proportions,

opacity stayed above 95% and moisture levels stayed within normal ranges, like conventional papers. The main noticeable differences appeared in whiteness and tensile strength. Tea stem recycled papers exhibited lower whiteness (brightness) than Xuan, hemp, or mulberry papers, and the whiteness progressively decreased as more tea stem was added. Among the different tea varieties, pu-erh tea stem paper had the darkest tone (lowest whiteness), while oolong tea stem paper was relatively lighter in color. This reduction in whiteness is expected given the presence of natural pigments and lignin in tea stems, which impart a light brown hue to the fibers.

In terms of strength, all samples showed a decline in tensile strength with increasing tea stem content. However, the severity of this decline varied: black tea stem paper retained strength exceptionally well, whereas green tea stem paper lost strength more rapidly. We identified 10% as an optimal tea stem proportion that achieved the highest tensile strength overall while only minimally affecting whiteness and other properties. At this low addition level, even the green tea produced paper with acceptable strength and quality, and black tea produced paper outperforming traditional Xuan paper in strength. These findings guided the selection of samples for the subsequent sensory study. In particular, paper formulations containing 10% tea stem fibers (with 90% auxiliary fibers) were chosen for further exploration, since they offered the best balance of mechanical performance and quality. The insights from the physical tests provide a foundation for understanding how the material might perform in real-world use and inform the design strategies discussed later in the paper.

5 CREATING MATERIALS EXPERIENCE VISION

Contemporary materials research suggests that excellent technical performance alone is not sufficient for a new material to achieve widespread adoption; the material must also offer a meaningful user experience. In the context of design, this means analyzing how a material feels, looks, and emotionally connects with users, and then leveraging those insights to guide design innovation. In this study, after establishing the physical viability of tea stem recycled paper, we turned to the exploration of its material experience. We employed approaches from Kansei Engineering and the MDD framework to create an experience vision for the material - a concise description of the desired sensory and emotional impact that the material should convey - and used that vision to inspire product design concepts.

5.1 Overview of Kansei Engineering Experiment

To systematically evaluate the sensory and affective impressions of the tea stem papers, we utilized Kansei Engineering techniques. Kansei Engineering, originally proposed by Kenichi Yamamoto in 1986, is a user-oriented product development methodology that seeks to quantify and translate people's feelings and perceptions (Kansei) into concrete design elements [9]. It provides an intuitive way to measure how materials or products are experienced by users. Professor Mitsuo Naga Machi, a pioneer of Kansei Engineering, described it as "a consumer-oriented technology for product development, a translation

technique that transforms customer feelings and intentions into design elements" [10]. In our research, Kansei methods allowed us to capture participants' emotional and sensory responses to different tea stem paper samples in a structured manner. We focused our sensory evaluation on two modalities that are most relevant for paper materials: vision (appearance) and touch (tactile feel).

The aim was to derive a set of descriptive attributes for the papers (rough/smooth, natural/artificial) and then determine the underlying dimensions (factors) that summarize the overall material experience. These dimensions would form the material experience vision and inform subsequent design decisions.

This sample size ($n = 20$) is considered adequate for factor analysis in exploratory studies, as it exceeds the commonly cited minimum ratio of 5 participants per variable.

5.2 Experimental Conditions

Considering the expected application scenarios for future tea stem recycled paper, this impression evaluation experiment focuses on the sensory experiences of touch and vision for users.

5.2.1 Participants

The participants in this experiment were 20 university students and teachers with design experience aged 19 to 55. These included 16 students aged 19 to 25 with equal gender distribution and 4 teachers aged 35 to 55 with equal gender distribution. Before the experiment, all participants were tested for their visual and tactile skills and none of them had any problems with visual or tactile skills.

5.2.2 Samples

The physical performance test results of tea stem recycled paper showed that recycled paper made from a combination of different types of tea stems and building tree bark fibers in the ratio of 1:9 (tea stem 10%: composite material 90%) performed well and had the best tensile strength. Therefore, four types of tea stems were selected for future product suggestions in this experiment: green tea stems, black tea stems, oolong tea stems and pu-erh tea stems, each with an addition rate of 10%, combined with fiber from Tree bark and building material waste paper pulp fibers, resulting in a total of 8 experimental paper samples.

5.2.3 Experimental Procedure

The impression evaluation experiment is divided into two steps. The first step is to collect the evaluation scale of tea stem recycled paper samples, screen them and create the SD Impression Evaluation Scale. In the second step, all samples are evaluated using the SD rating scale created, data is collected and data analysis is then carried out.

5.2.4 Evaluation Scale Collection Experiment

A total of 65 subjects took part in the experiment and there were 8 experimental samples. Of these, 60 valid data sets with a processing time of more than 90 seconds were

collected. The statistics for common vocabulary are shown in the following Fig. 10a.

Interestingly, completely opposite terms such as "thin" and "thick", "hard" and "soft" also appeared. In this experiment, we identified 13 pairs of sensory image vocabularies and constructed a survey questionnaire using a 7-point semantic differential scale. For example, taking "heavy-light", "brittle-flexible", and "soft-hard" as examples, as shown in Fig. 10b, these contrasting sensory picture word pairs were used as the two poles of the scale. They were classified into five levels, such as "very heavy", "moderately heavy", "neutral", "moderately light", and "very light", and subjects were required to provide detailed evaluations of the tea paper samples.

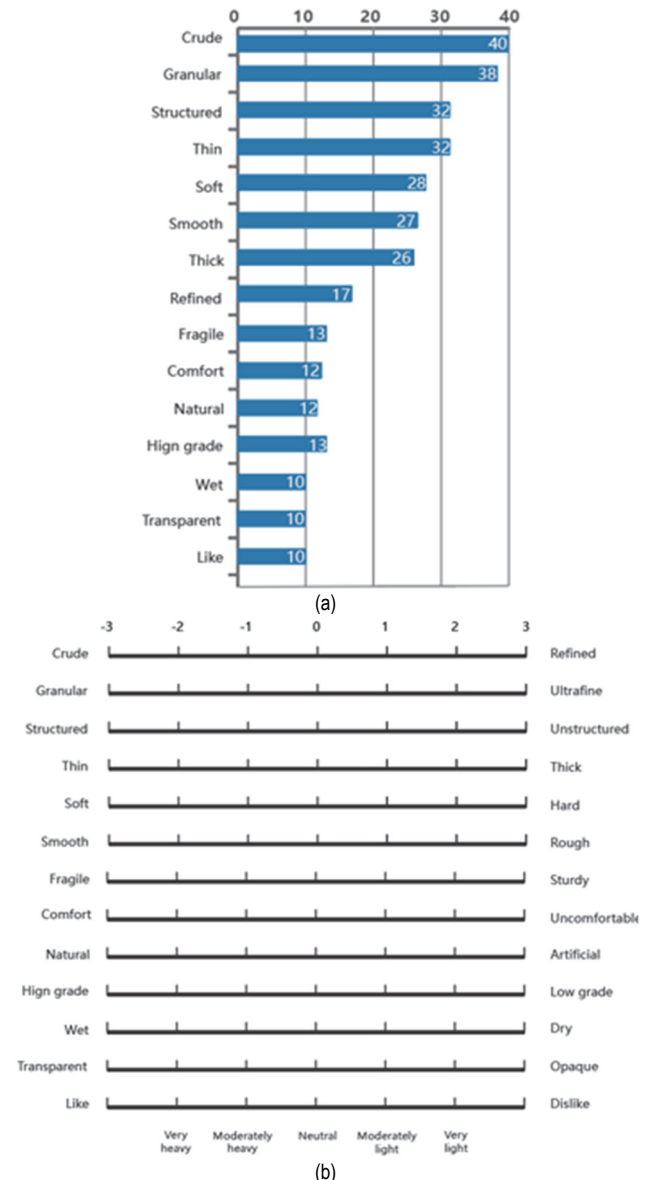


Figure 10 (a) Vocabulary summary list; (b) SD scale

5.2.5 Sensory Impression Evaluation Experiment

Using the above SD scale [11], the visual and tactile sensory impressions of the eight types of tea stem recycled paper samples were analyzed. As shown in Fig. 11, the experiment took place in the Human-Computer Interaction Laboratory of the Beijing Institute of Graphic Communication. The samples were placed in a 100 × 100

cm natural light box. Participants were given the opportunity to observe and touch the samples. After trying all the samples, they gave a rating for each sample.

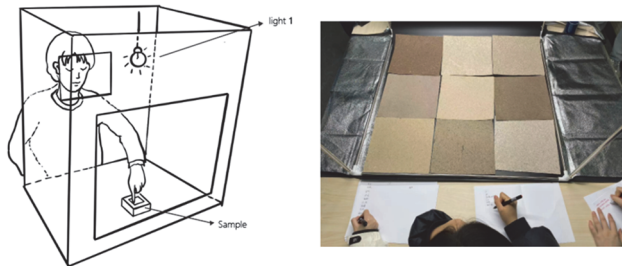


Figure 11 Experimental scene diagram

5.3 Factor Loadings

The collected SD assessment questionnaire data were imported into SPSS 2.6 software and factor analysis was performed using maximum likelihood and oblique rotation. Factor analysis revealed that the KMO value of the data was 0.762. A KMO value above 0.7 is generally interpreted as indicating good sampling adequacy, suggesting that the dataset is suitable for factor analysis.

Tab. 1 shows the factor loading information obtained after factor analysis, and shows that the first factor consists of four rating scales: "thin-thick", "soft-hard", "fragile-sturdy" and "transparent-opaque". Its eigenvalue reached 4.614, with a variance contribution rate of 30.881%. The vocabulary contained in this factor all describes the hardness and quality of the samples and is therefore summarized as a quality factor.

Table 1 Factor analysis loading values table

Evaluation Scale	Factor Loading		
	First Factor	Second Factor	Third Factor
Thick-Thin	0.954		
Soft-Hard	0.795		
Transparent-Opaque	0.563		
Fragile-Sturdy	0.892		
Pleasant-Unpleasant		0.685	
High grade-Low grade		0.814	
Natural-Artificial		0.469	
Like-Dislike		0.690	
Rough-Smooth			0.493
Granular-Ultrafine			1.016
Structured-Unstructured			0.566
Crude -Refined			0.471
wet-dry			0.423
Eigenvalue	4.614	2.047	1.360
Contribution rate	30.881%	9.415%	11.910%
Cumulative contribution rate	30.881%	40.296%	52.206%

The second factor consists of four scales: "pleasant-unpleasant", "high grade-low grade", "natural-artificial" and "like-dislike". Its eigenvalue reached 2.047, with a variance contribution of 9.415% and a cumulative variance contribution of 40.288%. The vocabulary in this factor describes the comfort and preference of the samples and is therefore summarized as a preference factor.

The third factor consists of five scales: "rough-smooth", "granular-ultrafine", "structured-unstructured", "crude-refined", "wet-dry". The eigenvalue reached 1.360, with a variance contribution rate of 11.91% and a cumulative variance contribution rate of 52.206%. The

vocabulary included in this factor all describes the surface texture of the samples and is therefore summarized as the surface texture factor.

5.4 Factor Scatter Plots

To better visualize the sensory experience effects of different samples, we calculated the common factor scores for each sample and presented them as factor scatterplots. Fig. 12 is a factor scatterplot with the first common factor (quality factor) on the x-axis and the second factor (preference factor) on the y-axis.

It can be seen that the recycled paper samples from four different tea stem varieties and waste paper pulp are mainly distributed in the second and fourth quadrants. In terms of sensory perception, they have qualities such as thick, hard and sturdy. In particular, the green tea stem samples, black tea stems and oolong tea stems combined with waste paper pulp fall into the second quadrant. Apart from being sturdy, they also evoke feelings of unpleasant, low grade and artificial properties and are generally not popular.

In contrast, the recycled paper samples from four different types of tea stems and tree bark are mainly distributed in the first and third quadrants. In sensory perception they show properties of thin, soft, fragile and transparent. In particular, the stem samples of green tea, pu-erh tea and oolong tea combined with tree bark fall into the third quadrant. They also convey the feeling of pleasant, high grade and natural properties and are very popular.

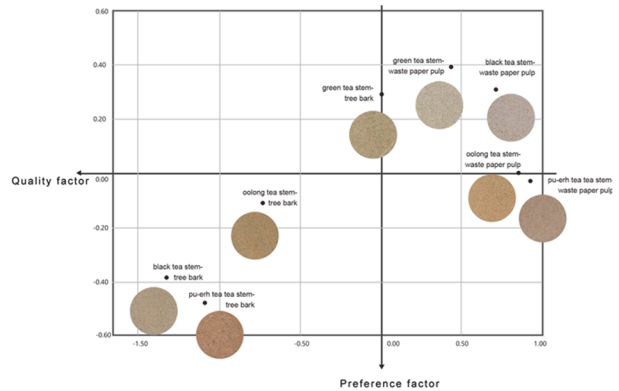


Figure 12 Factor scatter plots (quality factor and preference factor)

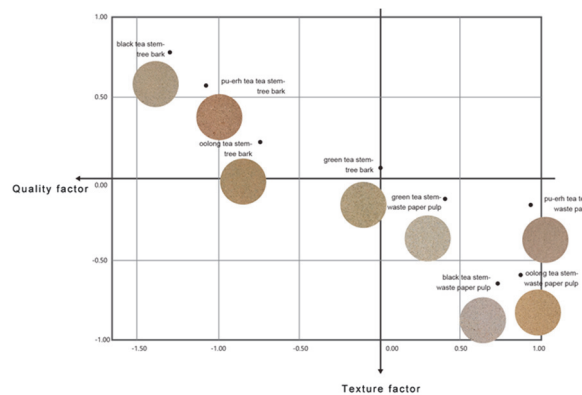


Figure 13 Factor scatter plots (quality factor and texture factor)

Fig. 13 is a factor scatterplot with the first common factor (quality factor) as the x-axis and the third factor (texture factor) as the y-axis.

It can be seen that the recycled paper samples from four different types of tea stems and waste paper pulp are predominantly distributed in the fourth quadrant. In sensory experience they exhibit qualities such as thick, hard, sturdy, opaque, rough, granular, structured, crude and dry.

In contrast, the recycled paper samples from four different types of tea stems and tree bark are mainly distributed in the first quadrant. They exhibit qualities such as thin, soft, fragile, transparent, smooth, ultrafine, unstructured and as well as moisture in the sensory experience.

6 MANIFESTING MATERIALS EXPERIENCE PATTERNS

Based on the results of the previous visual-tactile impression evaluation experiment, it is evident that there are significant differences in sensory experiences between tea stem-waste paper pulp and tea stem-tree bark recycled paper samples. This chapter provides an analysis of the design models for these two different sensory experience types. Below are the product design model diagrams for both types of samples.

6.1 Materials Experience Patterns of Tea Stem-Waste Paper Pulp Recycled Paper

Fig. 14 is the product design model for tea stem-waste paper pulp recycled paper. Based on the impression

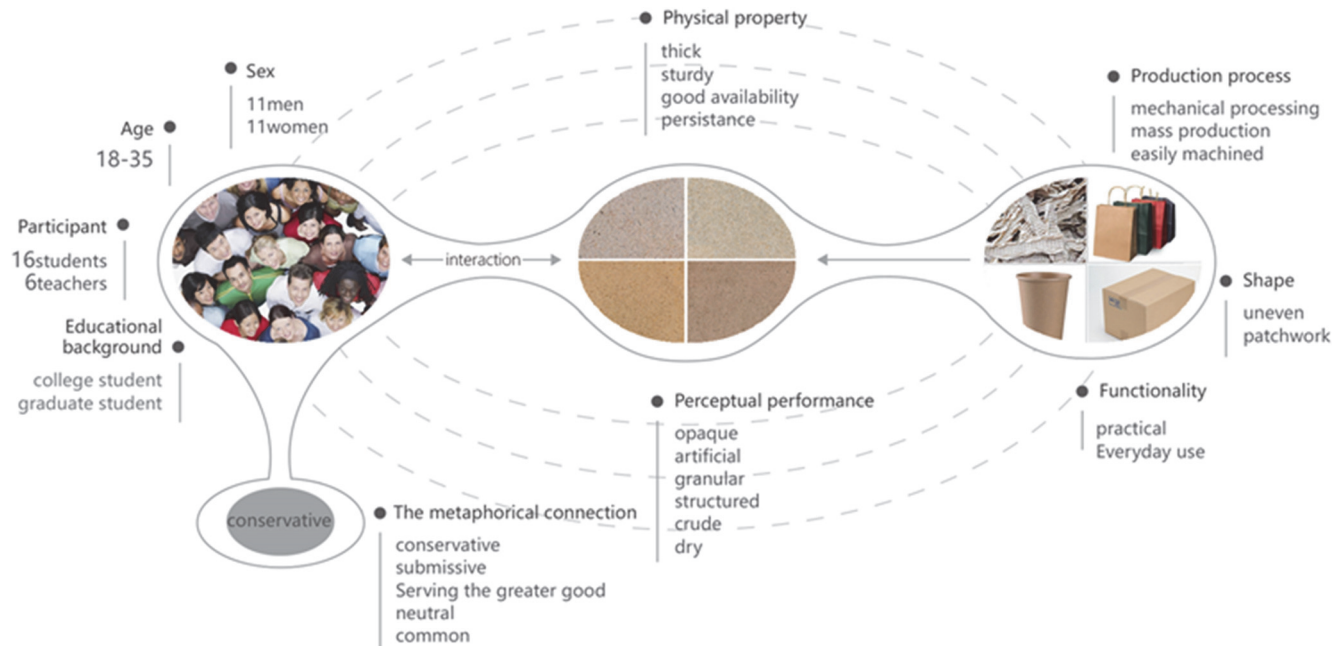


Figure 14 Product design model for tea stem-waste paper pulp recycled paper

6.2 Materials Experience Patterns of Tea Stem-Tree Bark Recycled Paper

Fig. 15 represents the product design model for tea stem-tree bark recycled paper. Based on the impression evaluation experiment results for tea stem- tree bark recycled paper, it is observed that the four types of tea stem combined with tree bark evoke a material experience characterized by thin, transparent, and a pleasant surface texture. Specifically, the green tea stem, pu-erh tea stem,

evaluation experiment results for tea stem-waste paper pulp recycled paper, it is observed that the four types of tea stem combined with waste paper pulp result in a material experience characterized by hard, rough and granular, but they receive lower ratings for comfort and preference. In terms of physical performance, tea stem-waste paper pulp recycled paper outperforms tea stem-tree bark recycled paper in terms of tensile strength. Considering its dual characteristics of physical performance and sensory experience, the experience that tea stem-waste paper pulp offers to users can be summarized as conservative, neutral and common.

Based on the intrinsic experiential sensations between users and materials, when such materials are used in product design, they should be used as practical, functional products. For example, they could be used as interior packaging paper for products, as interior cushioning material for fragile items, as industrial paper, or as hand-carry bags for everyday items. From a design perspective, irregular and compound shapes are suitable because these materials are intended for mass consumption and use. The production process should be simple, fast and efficient; in the future, mechanical production methods could also be used for production. In addition, artistic techniques such as dyeing, printing and engraving can be applied to the surface of these materials.

and oolong tea stem samples also convey feelings of comfort, high grade, preference, and a natural ambiance. In terms of physical performance, tea stem-tree bark recycled paper is comparable to tea stem-waste paper pulp recycled paper in terms of quantity, opacity, and moisture content. Although it lags in terms of whiteness and tensile strength compared to tea stem-waste paper pulp recycled paper, it still reaches the level of Xuan paper when the content is 10%.

Thus, it can be processed and used as a product. Considering its dual characteristics of physical performance and sensory experience, the experience that tea stem-tree bark offers to users can be summarized as attractive and high-grade. Given the intrinsic experiential sensations between users and materials, such materials, when used in product design, should be applied as products that prioritize artistic aspects. For example, they could be

used for brush calligraphy paper, product exterior packaging paper, creative furniture products, or decorative materials. The shapes should primarily be fluid and smooth to maximize the retention of the paper's surface characteristics and preserve its artistic qualities. The production process should also retain manual manufacturing methods to preserve its inherent texture.

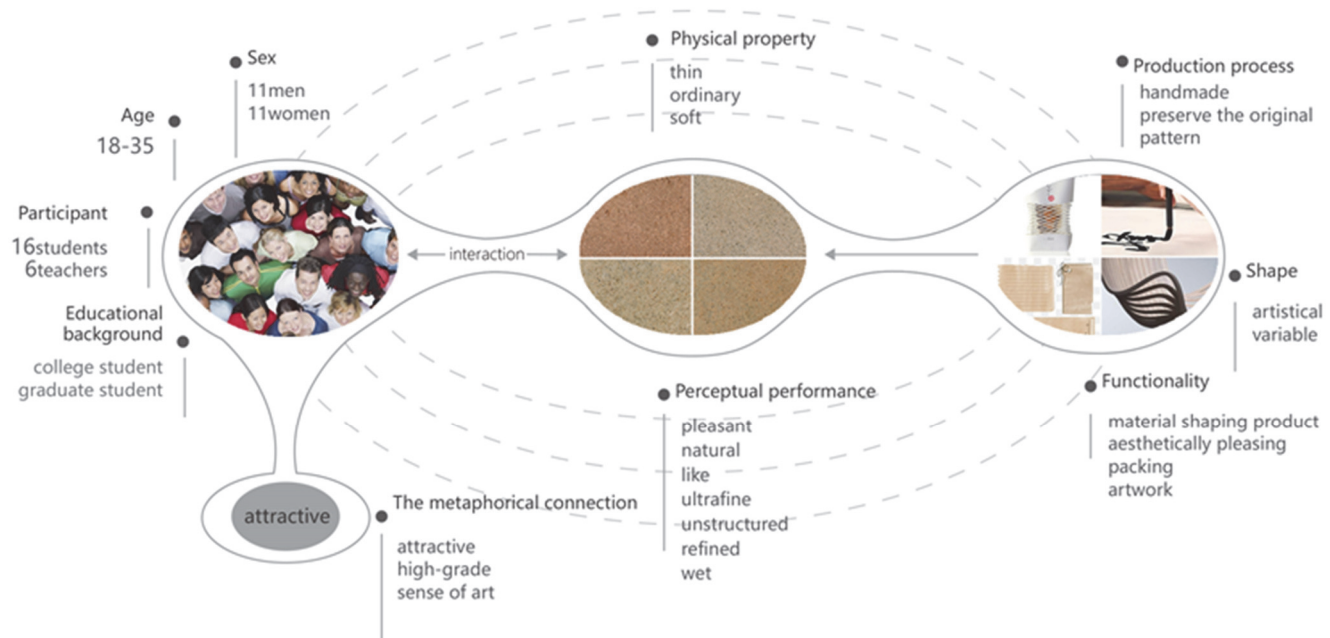


Figure 15 Product design model for tea stem-tree bark recycled paper

7 CONCLUSIONS

In this study, we explored the upcycling of discarded tea stems, a major by-product of the tea industry into recycled paper, integrating environmental sustainability with cultural value. We successfully fabricated various tea stem paper samples and evaluated their physical and sensory properties. A 10% tea stem content proved optimal. At this level, tensile strength was on average $12.3 \pm 0.4\%$ higher than Xuan paper. Maintaining opacity and moisture stability while even surpassing the tensile strength of some conventional papers. Differences among tea types (e.g., black tea for strength, green tea for color tone) suggest opportunities for property tuning. A key contribution is the development of a material experience vision: tea stem-pulp composites offered strength but a plain feel, while tea stem-bark composites were more delicate, natural, and preferred by users. These findings informed two design models, highlighting functional uses like packaging inserts and expressive applications such as cultural product wrapping.

While promising, the material faces limitations, particularly beyond 70% stem content where flexibility and strength decline. Current prototypes are handmade and not yet optimized for mass production. Future work will explore fiber treatment methods, long-term aging tests, and user-centered evaluations to refine performance and broaden applicability. Ultimately, this research offers a novel, sustainable approach to valorizing tea waste and contributes to material-driven design by connecting tradition, ecology, and innovation. These material property insights provide actionable guidance for future material

selection-functional, high-strength recycled papers may be prioritized for protective and structural applications, while aesthetically superior, fine-textured papers may be reserved for premium packaging and cultural products.

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