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Research on Sustainable Furniture Design Based on Waste Textiles Recycling

Yaolin Wang [1], Chenyang Liu [2], Xi Zhang [3] and Shaoting Zeng [4,*]

1 Kingston School of Art, Kingston University, Surrey KT1 2QJ, UK
2 Academy of Arts & Design, Tsinghua University, Beijing 100084, China
3 Department of Industrial Design, Hanyang University ERICA Campus, Ansan 15588, Republic of Korea
4 College of Art and Design, Beijing University of Technology, Beijing 100124, China
* Correspondence: sjmjzst@gmail.com

Abstract: As people's living standards rise, textile waste becomes more significant, and the number of waste textiles grows swiftly, wreaking havoc on the earth's ecosystem. Simultaneously, the creation of furniture consumes a significant amount of wood. The paint and adhesive used to manufacture it are also unsustainable and harmful to human beings. Therefore, one of the most urgent environmental challenges that needs to be paid attention to at present is the recycling of waste textiles and the sustainable recycling of furniture. Given this situation, this study proposes a solution combining sustainable design with composite material manufacturing. Guided by this solution, this study obtained a waste textile-starch composite material combining waste textiles, starch, and other components using microwave expansion technology. The material is biodegradable, environmentally friendly, and non-polluting. It can be customized to meet different design needs. Then, this research applies the material to sustainable furniture design and obtains a set of design works with sustainable characteristics. This kind of sustainable design scheme can eliminate the pollution and waste of waste textiles. At the same time, waste textile-starch composites can also serve as an economical and environmentally friendly alternative to many synthetic and natural materials used in furniture design and manufacturing. This reform scheme has a tremendous sustainable development promise and can simultaneously handle the problems of waste textile pollution and furniture resources.

Keywords: starch; waste textiles; furniture design; microwave expansion; material research and design applications; sustainable

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1. Introduction

Rising consumption levels, increasing per capita consumption of textile fibers, rapid turnover of fashion cycles, and the short lifespan of cheap textiles have led to the generation of large amounts of textile waste each year [1–4]. In 2021, the total processing of textile fibers reached 67.09 million tons in China [5]. Along with the high production of textiles, China can produce about 24 million tons of waste textiles each year, but less than three ten thousandths can be recycled [6]. Not only has this been observed in China, but it is estimated that Europe generates more than 95 million tons of textile waste annually [7,8]. Approximately GBP 140 million of wearable clothing is disposed of in landfills in the UK each year [9], with a large proportion of waste used clothing being landfilled or incinerated [10–12]. Excessive clothing consumption and waste have become a global problem [13]. If renewable resources continue to be consumed at this rate, future generations will face serious survival problems [14]. At the same time, the white paper, "Advances in recycling technology for waste textiles in China", estimates that chemical fibers account for 70% of waste textiles [15]. It is not straightforward for the earth to explain and digest chemical fibers. Therefore, from the perspective of sustainable development, textile waste must be considered and utilized as a resource to alleviate the current very critical situation [16,17].

The Classification and Code of Waste Textiles classifies waste textiles as cotton, wool, polyester, nylon, acrylic, mixes, and other types [18]. Natural fabrics quickly decay after recycling; cotton items typically require 1 to 5 months, wool products require 1 to 5 years, and silk products require approximately four years to break down. In contrast, artificial fiber woven products deteriorate more slowly or are even more challenging to decompose [19]. Nylon items typically take 30–40 years, and polyester products require 20–200 years [20,21].

Generally, the traditional methods of treating textile industrial waste are landfill and incineration [22,23]. However, the development of textile recycling and reuse technology can meet the current and future recycling business needs, reducing textiles' impact on the environment [24,25]. Among them, the treatment methods of recycling and decontamination include physical and chemical recycling treatment, such as thermal recycling technology, material recycling technology, and chemical recycling technology [26]. In addition, there are new treatment methods, such as the super-critical method [27], the ionic solution method [28], solid-state enzymatic hydrolysis [29], and enzymatic degradation [30]. In addition to the direct recycling and decomposition of waste textiles, waste textiles residue redesign is also popular in the apparel industry [31]. There are methods such as waste textile remaking, patchwork stitching, fabric transformation, and fabric decoration [32]. Nike has created the Move to Zero programs to promote sustainability [33], which recycles shoes, clothes, and other products into recycled plastics, yarns, and textiles, of which recycled materials can account for 70% of the product [34]. On the first level of Nike Town in London, England, there are numerous Move to Zero sneakers on exhibit. It displays the recycled materials, the processing, and the final product to the consumer. In addition, several clothing labels, including Rua Carlota [35], Everlane [36], Baserange [37], GAP [38], Levi's [39], C&A [40], Inditex group [41], and Nude Jeans [42] featured or developed a line of sustainable apparel to contribute to the sustainability of waste textiles fabrics [43].

With the pollution and waste of waste textiles, the waste and pollution of furniture is also very serious. Association (UEA), 80% to 90% of EU furniture waste in Municipal Solid Waste (MSW) is burned or sent to landfill. Only 0.3% of second-hand furniture was recycled [44]. In Australia, the average household discards 24 kg of furniture annually, two-thirds of which are made of wood, and the rest are sofas and armchairs [45]. Generally, the furniture consists of many parts, including wood, metal, and various plastics, making the recycling process extraordinarily complex and challenging [46,47]. In addition, most of the furniture on the market is made of particleboards containing toxic chemical adhesives, which even contain harmful chemicals, such as flame retardants [48]. These materials are almost impossible to recycle and are difficult and expensive to handle [49]. The current situation of waste furniture is thought-provoking. Therefore, replacing the materials for furniture production and reducing the waste of resources and environmental pollution in the process of furniture production and use are also important issues that people should consider.

In terms of sustainable utilization of waste furniture, it is a feasible method to finish and repair some old furniture with better quality [50]. However, this method has poor effects and limitations. For example, the repair cost is sometimes twice or three times that of new furniture, and the use of repair materials is also elementary to cause waste [51]. In addition, recycling waste furniture materials and producing green and sustainable furniture have become effective means for some countries to promote the value chain of ecological and "green" products [52]. For example, IKEA provided its "People and Earth Positive" sustainable development plan [53], which is committed to recycling and using renewable resources to make furniture. First, ecological materials must be used for furniture construction [54]. Second, processing, recycling, and destruction should discharge pollutants as little as possible to minimize environmental damage [55]. Finally, furniture design must meet consumer expectations and maximize durability. Materials can still be recycled and reused when furniture is wasted to realize a circular economy [56].

With the continuous deepening and development of research in recent years, many scholars have found that waste textiles can be used for furniture, construction, and other purposes [57]. On the one hand, this method can recycle waste textiles. On the other hand, it can also reduce the use of raw materials for furniture production and significantly save natural resources. For example, Professor Veena Sahajwalla, founder of the Centre for Sustainable Materials Research and Technology (SMaRT) at the University of New South Wales, mixed the fabric with broken glass and pressed it into sheets. These plates can be used for building, industry, and furniture [58,59]. Zunjarrao Kamble and Bijoya Kumar Behera manufactured a new composite material from waste cotton textiles by laminating unidirectional glass fiber preforms with needled jute nonwovens. This material has sufficient thermal stability and can replace moderately priced and inexpensive wood in furniture, construction, and construction materials [60]. In addition, some designers combine fabrics with bioplastics to make furniture panels [61], such as tables and chairs [62]. Designers use various technologies and materials to rejuvenate Waste textiles and create more sustainable solutions for furniture design.

However, in applying waste textiles to furniture design and manufacturing, most scholars only study the recycling of textiles from the perspective of material research and use them for furniture product manufacturing. The process lacks systematic design strategies as guidance. Moreover, consumers have some doubts about the safety of recycled products. The recognition rate of consumers for this behavior is low. At the same time, its related manufacturing process is relatively complex, and the cost of auxiliary materials is high. More importantly, at present, few people use the strategy of sustainable design based on material research and development, and use it for design applications to solve the problems of waste and pollution of waste textiles and waste and pollution of waste furniture at the same time.

Therefore, to solve the above problems, this study aims to apply a sustainable design strategy to redesign and manufacture furniture and to incorporate textile waste into the design of environment-friendly furniture by combining other materials and using appropriate technology. First, "sustainable design" is the core design principle of this project. "Sustainable design" originates from the concept of sustainable development [63] and is the in-depth thinking of the design community on the relationship between human development and environmental challenges [64]. Since the 1980s, sustainable design has been actively guiding the design of all types of sustainable products, services, structures, environment, and social systems and has become a strategic activity to promote sustainable transformation [65,66]. Sustainable design theory contains much knowledge about how to solve environmental and social problems by rethinking industrial products and processes and how organizations play a role in a more sustainable socio-economic structure [65,67–69]. Second, the sustainable design focuses on the experience and feelings of consumers. It is essential for consumers to embrace and purchase environmentally sustainable materials. It was discovered that consumers in developed countries are more familiar with and accepting of sustainable and recycled items [70], whereas consumers in other countries and regions generally have favorable attitudes about recycled products [71]. Notable is the fact that British consumers prefer recycled products to non-recycled products of comparable price and quality [72]. Therefore, the application of sustainable design and the creation of recycled materials are ecologically desirable and have market development potential [73]. Thirdly, the scheme uses starch as auxiliary material to synthesize textile waste into a composite material and use it for furniture design. According to previous studies, starch is mainly used as a sizing agent in the textile industry, while modified starch is mainly used as material for warp sizing, printing sizing, and fabric finishing agent [74]. In addition, pre-gelatinized starch can be used as an adhesive, thickener, and stabilizer in construction. Therefore, using starch as auxiliary material has the advantages of low cost and convenient manufacturing.

Under the guidance of the sustainable design concept, firstly, this paper studies the sustainable reuse of waste textiles materials through experiments supported by relevant theoretical basis to produce complex, light, porous, and sustainable starch textile fiber composites. In this process, the performance and sustainability of waste textile-starch composites used in furniture design and production are emphatically analyzed. Secondly, this material with unique characteristics is applied to sustainable furniture design, and the possibility of solving the problems of waste textile pollution and waste furniture is also explored in this way.

2. Methods

2.1. Design Method Process

The design research methods of this project mainly focus on material research with method support and design application research. Method support includes starch gelatinization and gel, the principle behind microwave expansion technology, and the effect of microwave expansion on starch. The material research includes the selection of experimental equipment, the change of state at different heating times, the starch experiment, the fabric experiment, the ratio experiment, and the durability test of composite materials. The primary purpose of material research is to test whether the performance of materials can support the design and manufacture of furniture and whether they have pollution-free and sustainable characteristics. The description of material properties will be the core content of material research. It is the core point to demonstrate whether the waste textile-starch composite material is pollution-free and sustainable and whether it can replace natural materials to become furniture design and manufacturing. This core point is also the key to the effectiveness of the solution proposed in this paper. Based on the research results of material characteristics, the design research mainly focuses on designing the shape, function, and use of furniture according to specific requirements and displaying the sketches and results (Figure 1). Finally, the step of the design process is to summarize the effect of the solution on solving the pollution and waste of waste textiles and waste furniture.

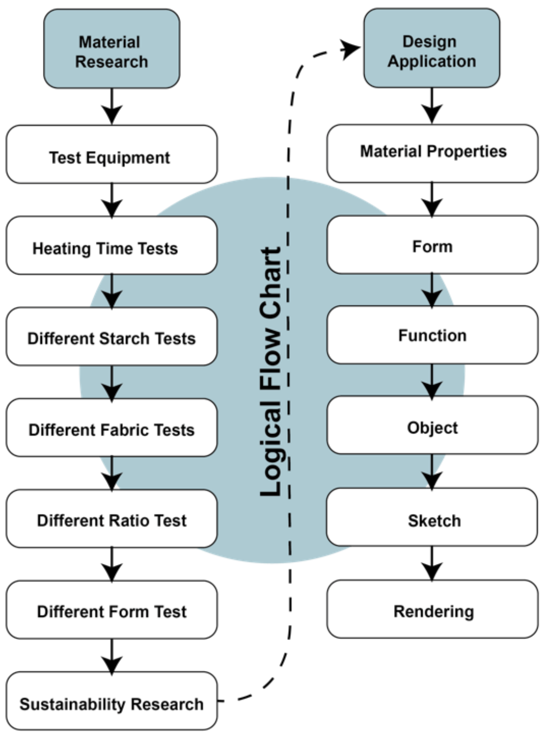


Figure 1. Sustainable design solution flowchart.

2.2. Experimental Equipment and Steps

The experimental device consists of scissors, a microwave oven, a circuit breaker, an electronic scale, a heating container, a weighing container, a stirring rod, a stirring container, and a hardness tester (Table 1). Material production steps: cutting fabric; decomposing the fabric; placing the fabric in the container; adding the specified amount of starch and water;

fully stirring; placing the container in the microwave oven; heating; cooling and molding (Figure 2). In addition to the microwave oven as the baking equipment, the air fryer and oven were also tested. However, the finished material is not sticky, has an insufficient hardness, and cannot expand. Therefore, it further proves the feasibility and flexibility of using microwave expansion technology.

Table 1. Experimental equipment.

Scissor	Stirred Vessel	Muddler	Container	Heated Container	Electronic Scale	High Speed Blender	Microwave Oven	Durometer
								

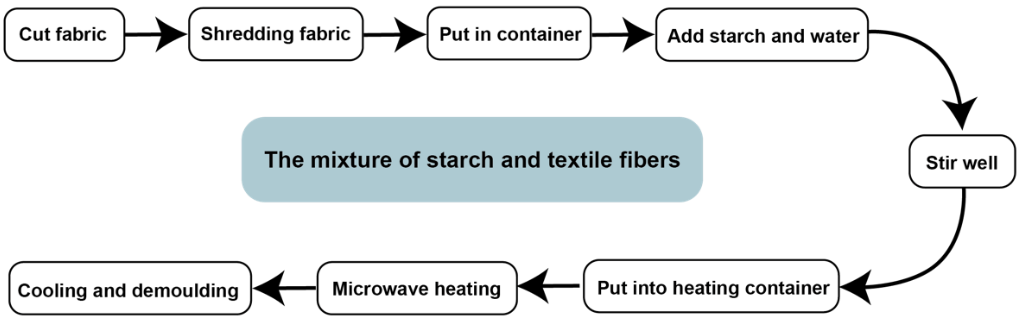


Figure 2. Material manufacturing steps.

2.3. Paste and Gelation of Starch

Starch is a natural renewable polymer resource; when starch is mixed with water and the water temperature rises above 53 °C, the physical properties of starch change significantly [75]. Raw starch is a cluster of microcrystals organized radially. When heated in the presence of water to soften and expand, the starch begins to form a paste at a particular temperature range. During this process, starch granules are broken down into a solution of polymers, which is referred to as dextrinized starch [76,77]. Gelation happens when starch turns dry because of a particular chemical or physical action [78]. During the gelation process, starch exhibits a transparent or translucent viscous viscosity, which varies depending on the kind of starch [79]. The viscous liquid eventually becomes elastic and robust as more water is lost, but as it continues to lose water, it loses its elasticity, dries up, and its volume decreases proportionately [80]. The drying of starch milk goes through a series of continuous changes of "pasting → initial gelation → gel water loss → gel nucleation → gel drying and shrinking". The water in the process of change is the medium for the reaction of starch, and sufficient water and high temperature accelerate the gelation of starch slurry in forming [81]. The starch gelation process is an irreversible rearrangement of the molecular chain, and the gelatinized starch particles lack the crystallinity of the original starch and can be expanded without solubility [82]. Therefore, the gelatinized starch granules are water-insoluble, can be stored for an extended period, are difficult to degrade, and can be utilized in a variety of applications.

Different plant starches have distinct properties and pasting qualities. The pasting enthalpy of potato starch was greater than that of cassava and sweet potato starch, and the mixture of cassava starch and potato starch had the highest viscosity value, while cassava starch and its mixture had the lowest roughness [83]. Based on the findings of the textural investigation, potato starch gels were more rigid and viscous than corn and tapioca starch gels [83].

2.4. Microwave Puffing Technology

Microwave puffing technology uses the radiation conduction of electromagnetic energy so that its transmission to the interior of the material is absorbed by the moisture while instantaneously converting into heat, resulting in the violent vibration of molecules and the acquisition of kinetic energy to achieve the vaporization of water [84]. The microwave energy penetrates the material so that the polar molecules within the material friction and internal heat, so that the liquid inside the processed material instantly heated vaporization, pressurization, and expansion, and relying on the expansion force of the gas to polymeric material structure changes in the components, and become a net-like tissue structure characteristics, stereotypical porous material [85,86]. The more the microwave power, the greater the evaporation rate of water, and hence the greater the number of holes [87]. Expansion of the material is primarily determined by the material's physical and chemical qualities as well as the development of a specific texture to enable the wrapping of water vapor and the building of pressure [88]. In addition, it also relies on its dielectric properties to absorb microwave energy effectively into thermal properties [89].

Microwave puffing technology is characterized by high energy conversion efficiency and fast heating speed [90]. The microwave puffing process has a sterilizing effect. Microwave sterilization is conducted under the combined influence of thermal and non-thermal factors. A good sterilizing result can be achieved at a lower temperature and in a shorter amount of time than with standard temperatures [91].

2.5. Effect of Microwave on Starch

According to the research results of Lewicka et al. [92], the principle of microwave expansion can also act on starch. Microwave heating can change the structure of starch particles. After microwave heating, the starch particles will deform, break, and disintegrate [92], making the volume of starch-solidified products expand and the structure loses. In addition, the water absorption and water retention of starch after microwave treatment are significantly improved, so the starch after microwave heating has good water absorption and water retention [93] and is not easy to melt.

Ndife et al. observed in their study of microwave radiation of wheat, maize, and rice starches that gel and chalky zones were produced when the ratio of starch to water was 1:1, and only gel zones were produced when the ratio of starch to water was 1:115 and 1:2 [94]. These studies show that the water content of starch has an essential effect on microwave radiation starch. The higher the moisture content of starch, the stronger the ability to absorb microwaves and the more violent the evaporation of water in it when the starch is heated [95]. In microwave-dried potato starch, the viscosity reduces dramatically, and the gelation temperature remains stable; when the water content is between 20% and 35%, viscosity decreases to a lesser extent, and the gelation temperature rises [96]. In addition, microwave energy has a more significant impact on microwave heating starch. When the microwave energy is too high or the heating time is too long, starch will occur a coking phenomenon [97].

3. Results

3.1. Study of Starch Composites

3.1.1. Study on the Change of Material Heating State

According to Table 2, during the microwave heating process, the water in the waste textile-starch mixture began to evaporate rapidly, while the whole object gradually expanded and filled with bubbles and small holes. After a certain degree of expansion, the waste textile-starch mixture will not continue to expand but gradually dry and shrink slightly. After the water is completely evaporated, the mixture starts to scorch from the inside and bottom. Therefore, heating time is a very critical control variable. The research on the state of a starch mixture under different heating times shows that the expansion, hardness, dryness, and wetness of starch mixture under microwave heating vary with the length of heating time, which helps to prepare composite materials for design by controlling the heating time according to the design requirements.

Table 2. State change of waste textile-starch mixture under different heating time.

Time	Status Change
1 min	The starch gelatinizes, and the outside of the wrapped fabric begins to dry.
2 min	The starch gel becomes translucent, starts to expand, gets larger, and still has much water in it.
3 min	As the mixture continues to grow, the surface becomes essentially dry, soft, and elastic, with many tiny bubbles.
4 min	The mixture stops getting more extensive and basically dries and hardens.
5 min	The mixture is dry and firm.
6 min or more	The water has evaporated, and continued heating will start to scorch from the middle and bottom.

Note: This test uses 5 g of fabric 20 g of starch 20 g of water as the sample.

3.1.2. The Effect of Different Kinds of Starch on Waste Textiles-Starch Composites

Table 3 shows that corn starch, wheat starch, cassava starch, potato starch, sweet potato starch, pea starch, mung bean starch, and glutinous rice flour are selected as experimental materials to make starch composite materials. The experimental results show that the material state of different types of waste textile-starch mixtures has both similarities and differences. Waste textile-starch mixtures based on pea starch, corn starch, mung bean starch, and wheat starch have low consistency and are not easy to expand, stiffen, and aging. The waste textile-starch mixture based on cassava starch, potato starch, sweet potato starch, and glutinous rice flour, although difficult to manage in morphology, shows greater expansibility and a more porous structure. This phenomenon provides a variety of options for the development of design applications. This characteristic enables the design scheme to prepare composite materials for design by blending different kinds of starch according to different design requirements based on sustainable environmental protection characteristics.

Table 3. Microwave swelling effect of different kinds of starch and the same textile fiber in the same ratio.

	Pea Starch	**Corn Starch**	**Mung Bean Starch**	**Wheat Starch**	**Cassava Starch**	**Potato Starch**	**Sweet Potato Starch**	**Glutinous Rice Flour**
Types of Starch								
Textile Pieces								
Hybrid Materials								

Table 3. *Cont.*

	Pea Starch	Corn Starch	Mung Bean Starch	Wheat Starch	Cassava Starch	Potato Starch	Sweet Potato Starch	Glutinous Rice Flour
Characteristic	Slightly inflated, tasteless and expensive	Slightly swollen, a little odor, smooth sides	Dilation, tasteless, smooth on the sides, expensive	Slightly inflated, tasteless	Large expansion, bottom center depression, tasteless, porous	Large expansion, bottom center depression, tasteless, porous, a little odor	Large expansion, bottom center depression, tasteless, porous	Large expansion, odorless, porous, enquiring more moisture and heating time
Weight	34.1 g	34.7 g	34.7 g	34.0 g	35.2 g	35.1 g	34.8 g	34.6 g

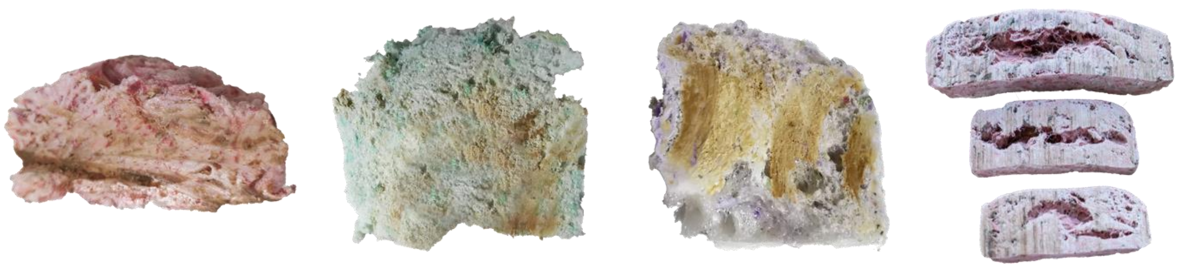
3.1.3. Influence of Material Composition Ratio on Waste-Textiles Starch Mixture

The status of the waste-textiles starch mixture created by various percentages of textile fiber, starch, and water was experimentally tested, as shown in Table 4. Results that cannot be created or have a minor difference are not displayed here. Although these proportions can produce solid blocks, the experimental results reveal that 1:2:3 and 1:4:4 proportions can provide a superior quality finished products and are easier to convert into a more fixed shape. Simultaneously, when the design requires the use of solid materials, the ratio of 1:2:3 can be used for manufacturing; when the design requires the use of loose, porous, thick, and light materials, the ratio of 1:4:4 can be employed.

Table 4. Experimental effects of different ratios of textile fiber, starch, and water.

Ratio	**1:1:2**	**1:2:3**	**1:3:3**	**2:1:3**	**2:2:3**	**1:4:4**	**1:5:5**	**1:7:7**
Mixture								
Characteristic	Slightly loose edges, no expansion	Sturdy and firm, no expansion	Sturdy and firm, slightly expanded	Loose edges, no expansion	The edges are not firm, no expansion	Sturdy and strong, Inflation	Firm, Inflation, slightly hollow at the bottom, starchy on the outside	Large expansion, slightly hollow at the bottom, too much starch on the outside
Weight	9.2 g	15.5 g	26.0 g	13.9 g	13.3 g	28.6 g	34.8 g	45.2 g

Meanwhile, although the material has a porous structure, the internal structure of mixtures created with varying proportions and constituents differs. Figure 3a–c depict the cross-sections of the compound formed by combining cloth, starch, and water in varying proportions. Figure 3d depicts the fabric, starch, water, and diatomaceous earth mixture. As depicted in the figure, the cut surface of the 1:2:3 ratio is relatively compact, with few pores, and smooth and flat (Figure 3a); the cut surface of the 1:4:4 ratio has more pores and uniform distribution, with a slightly rough texture (Figure 3b); the cut surface of the 1:6:6 ratio has significant and many pores with uneven size distribution (Figure 3c); and the cut surface of the 1:6:10:6 ratio is hollow inside, with tiny pores of varying size. Diatomaceous earth composite materials were distinct (Figure 3d). Different ratios and compositions of materials have their properties, can suit various design requirements, and can be selected based on the use case. The 1:2:3 and 1:4:4 ratios have greater economic efficiency and resource conservation in terms of cost and resource use.



(**a**) (**b**) (**c**) (**d**)

Figure 3. Profiles of different scale composites. (**a**) 1:2:3 ratio. (**b**) 1:4:4 ratio. (**c**) 1:6:7 ratio. (**d**) 1:6:10:6 ratio.

3.1.4. Effect of Different Waste Textile on Starch Composites

Waste textiles are the main component of waste textile-starch mixtures; therefore, different types of waste textiles will also affect the performance of waste textile-starch mixtures. Due to the wide variety of fabrics, it is difficult to determine the composition of recycled waste fabrics, and there are no strict requirements for the composition of fabrics processed by materials. Therefore, in this study, they are roughly divided into fabrics that are easy to decompose into fibers and fabrics that are not easy to decompose into fibers. The experimental results in Table 5 show that the starch distribution of the fabric that is easily decomposed into fiber is uniform, and the bottom is flat; the starch distribution of the fabric that is not easily decomposed into fiber is uneven, and the bottom is easily sunken upward in the middle. Among them, the fabrics of the fourth and seventh experimental samples were tough to be decomposed into fiber-like fabrics, and the surface of the finished materials produced could be seen as many flaky rags as possible with unique textures and appearances.

3.1.5. Study of Different Forms of Waste Textile-Starch Mixtures

According to Table 6, the state of the waste textile-starch mixture in different forms was investigated by experiments. The experiments showed that the transformation of composite material from semi-solid to solid can be molded with the aid of different-shaped molds that have the properties of high plasticity and ease of molding and can match a variety of design specifications. If they can withstand microwaveable heating and are easy to release, a variety of mold materials are available, including PET resin, polyethylene, silicone, and others. Depending on the result, puffing can be followed by a second shaping using mechanical cutting, grinding, or other cold processing techniques. This feature greatly expands the freedom of design and can make the design scheme more diversified and more prosperous.

Table 5. The microwave puffing effect of different waste textiles and the same proportion of starch.

	A	B	C	D	E	F	G	H	I
Textile									
Broken									
The top of the mixture									

Table 5. *Cont.*

	A	B	C	D	E	F	G	H	I
The bottom of the mixture									
Charact-eristic	Easy decom-position into fibers, uniform distribution of starch in the mixed material, flat bottom	Easy decom-position into fibers, uniform distribution of starch in the mixed material, flat bottom	Easy decom-position into fibers, uniform distribution of starch in the mixed material, flat bottom	Not easily decomposed into fibers, uneven distribution of starch in the mixed material, concave in the middle of the bottom	Not easily decomposed into fibers, uneven distribution of starch in the mixed material, concave in the middle of the bottom	Not easily decomposed into fibers, slightly uneven distribution of starch in the mix, slightly concave in the middle of the bottom	Not easily decomposed into fibers, uneven distribution of starch in the mixed material, concave in the middle of the bottom	Easy decom-position into fibers, uniform distribution of starch in the mixed material, flat bottom	Not easily decomposed into fibers, slightly uneven distribution of starch in the mix, slightly concave in the middle of the bottom
Weight	26.4 g	27.6 g	28.3 g	24.6 g	25.1 g	26.4 g	25.7 g	25.2 g	35.3 g

Table 6. Morphological analysis of waste textile-starch mixture.

Samples	Form	Manufacture Method	Characteristic	Availability
	Irregular arcs	Mold shaping	Simple shape, easy to shape	High
	Multiple arcs	Mold shaping	Simple shape, easy to shape	High
	Arc + straight shape	Mold shaping + cutting	Secondary processing after forming	High
	Arc bottom columnar	Cling film + mold shaping	Shape can be controlled, easy to shape	High
	Rod-like	Mold shaping	Shape is not easy to control, can be out of shape	Low
	Cylindrical, cup-shaped	Double mold shaping	Easy to form	Medium

3.1.6. Mechanical State Assessment of Waste Textile-Starch Blends

The different material mechanical states were further evaluated experimentally in Figure 4 and Table 7.

Although the volume, appearance, and internal structure of the microwave-expanded material of starch and textile fiber were comparable to those of the microwave-expanded product of a single starch, the waste textile-starch mixture was significantly denser and more rigid than the single starch material. After microwaving a single starch, the solid becomes more brittle, porous, and readily crushed (Figure 4). Due to the mechanical qualities of textile fibers, such as increased strength, the addition of textile fibers can significantly increase their hardness and strength, making them more durable and less prone to damage. Hardness tests were performed by using Shore C Durometer for different starch composites, fiber-based textile composites, and sheet-based textile composites. Each sample was evaluated five times independently, and the mean value was determined (Table 7). The test findings revealed that the hardness of the various types varied slightly, but nearly all the composites had a hardness greater than 95 (HC). Therefore, the starchy textile fiber substance is adequately rigid for designing different things.

Figure 4. The shape of Single starch microwave expanded solid.

Table 7. Shore C Durometer measurement results.

	Only Starch	Pea Starch Mixture	Corn Starch Mixture	Mung Bean Starch Mixture	Wheat Starch Mixture	Cassava Starch Mixture	Potato Starch Mixture	Sweet Potato Starch Mixture	Glutinous Rice Flour Mixture	Mixture of Fibers	Flaky Mixture
Hardness (HC)	85.5 93.5 87.5 90.5 91.5	79.5 105.5 90.5 104.5 105	93 95.5 107.5 102.5 110	102.5 92.5 97.5 99 108.5	94 95 92 96.5 102.5	97.5 100 92.5 103.5 94	90 97 100.5 108 100	94 101.5 93.5 100 105.5	90.5 104 97.5 96.5 95	109 96 99 103 105	99 97 99.5 95.5 94
Mean Value (HC)	89.7	97	101.7	100	96	97.5	100.9	98.9	96.7	102.4	97

3.1.7. Testing of Additional Properties of Waste Textile-Starch Composites by Mixing Other Auxiliary Materials

In addition to starch, the material can be supplemented with other ingredients as required. For example, activated carbon, diatomaceous earth, and activated carbon plus diatomaceous earth are added additionally in Figure 5a–c, respectively. Activated carbon itself, with countless tiny pores, has the function of physical adsorption and chemical adsorption, which can play the role of adsorbing harmful substances and purifying the air, and deodorizing [98]. Diatomaceous earth also has strong adsorption, lightweight and high-impact strength, and compressive strength [99]. The addition of these two substances can enhance this material's adsorption capacity and strength, which can be applied in fields such as air purification.

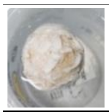
(**a**) (**b**) (**c**)

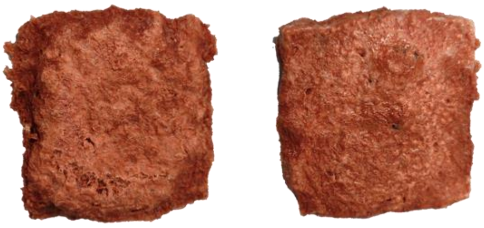
Figure 5. Samples of composite materials were added with activated carbon (**a**), diatomaceous earth (**b**), and a mixture of activated carbon and diatomaceous earth (**c**), respectively.

3.1.8. Sustainability Analysis

According to Table 8, the recyclability of waste textile-starch composites is further understood through experiments. When the waste textile-starch composites are wasted after use, the material can be decomposed by rinsing and soaking to separate the starch soaked in the wrapped fiber fabric. The research found that this mixture sample becomes loose when soaked in water for more than 24 h, and the soaked starch appears as a solid gel that can be separated from the fabric fibers by squeezing, and the residual starch gel does not affect the secondary production. The longer the soaking time, the higher the starch gel fractionation. In the experiments, soaking in cold and hot water was tried separately, and it was found that the starch dissolved more rapidly in hot water but formed a more pronounced gel and did not separate easily from the fibers compared to cold water soaking. The separated fabric fibers could be reused by forming a mixture with new starch and reusing it (Figure 6).

Table 8. Material decomposition process.

	Start of Soaking	**Soaking 12 h**	**Soaking 24 h (Squeezing)**	**Drying**
Soak in cold water (20 °C)				
Soaking in hot water (100 °C)				



(**a**) (**b**)

Figure 6. The sample of waste textile-starch composite material after being decomposed into materials. (**a**) front; (**b**) back.

Therefore, a waste textiles-starch mixture is a sustainable material composed of waste textiles and plant starch. Figure 7 shows the whole life cycle of the waste textiles-starch mixture, from the recycling of waste textiles to the processing and manufacturing of composite materials, to the recycling and remanufacturing, to the de-composition and grading of products after they are no longer helpful. The whole production process is non-toxic and harmless and emits no pollution to the environment.

3.2. Furniture Design Applications

3.2.1. Exploring How to Achieve Sustainable Furniture Design According to the Material Properties

According to the above research, the various excellent properties of waste textiles–starch composites, such as rigidity, strength, degradability, and adsorption capacity, can be used for the sustainable design of furniture following the principle of design to reduce the waste of natural resources of furniture and the problem that waste furniture cannot be recycled. This is a sustainable material-driven design process. It emphasizes the use of the material itself to its full advantage and significantly impacts the product's appearance, structure, and function.

The waste textiles-starch composites have the fabric's natural texture, and their appearance is slightly rough. The designer can keep the rough surface or make it smooth by grinding and polishing. Because this material is composed of textile fibers, it can also visually represent textiles' softness and warmth retention. Starch fabric composite is a solid porous material with high strength and bearing capacity, which is suitable for the structural requirements of furniture. In addition to these essential qualities, variable proportions, starch, and additives make these materials slightly different and can meet the different needs of furniture design. Additionally, due to their porosity, waste textiles-starch composites have the functions of sound absorption, lightweight, and heat insulation. In terms of sustainability, the material is non-toxic, pollution-free, and recyclable to achieve sustainability. Therefore, in the process of product assembly and application, the use of non-degradable and toxic adhesives or coatings should be avoided so that the product's sustainability is not a gimmick but an actual green environmental protection product. This design can use integral furniture, mortise and tenon, modular design, and other structures that do not need adhesives. When the adhesive is needed, starch gel heated by microwave may be regarded as an adhesive.

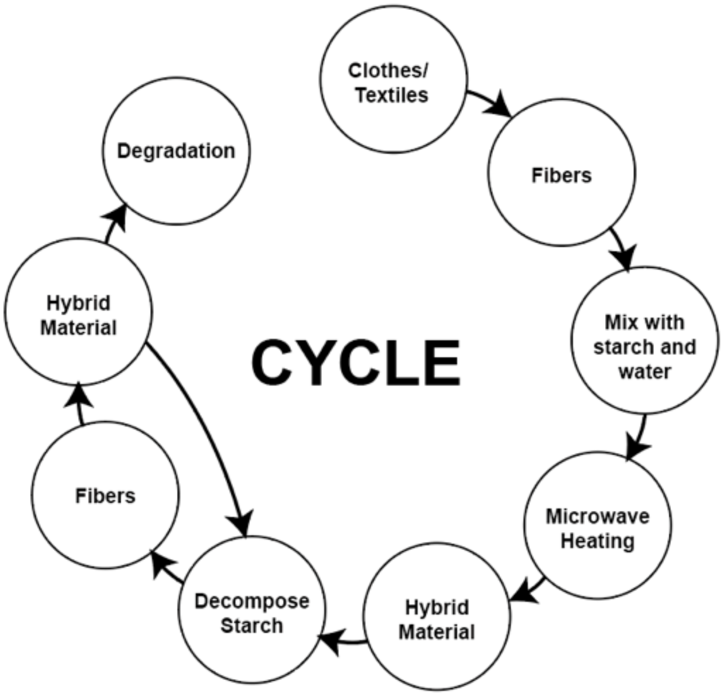
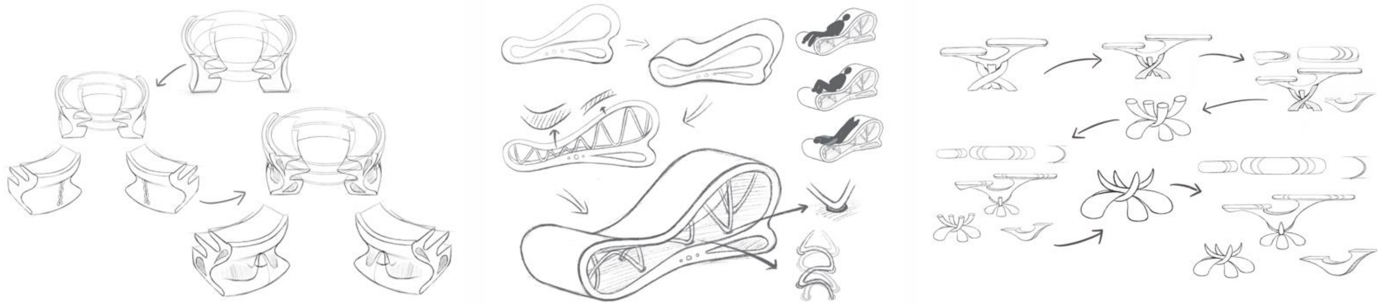


Figure 7. Illustration of the life cycle of waste textile-starch composites.

3.2.2. Sustainable Furniture Design Sketches and Final Solutions

Based on the evaluation of waste textile-starch composites, it is possible to determine that the material is suitable to produce furniture such as tables, chairs, cabinets, shelves, and wall decorations. It is also capable of producing dividers, sound-absorbing panels, and sandwich panels. Furthermore, given the drawback that the material should not be immersed in water for an extended period, the design strategy chose to make furniture such as interior tables and chairs the representative design item. Because the design application technique must avoid the use of chemical gums and other non-environmental and non-biodegradable materials, the design solution employs a one-piece shape with nested and bracketed top and bottom structures. Through the attempts in the design process, as shown in Figure 8, the design scheme finally pushed out several sets of relatively reasonable drafts.

Similarly, in this design plan, waste textiles-starch composites are combined with glass and aluminum alloy to complement and increase some functions that this material cannot perform. It also improves the aesthetics and structural integrity of the finished furniture. Furthermore, glass and aluminum alloy are environmentally friendly materials that can be recycled and reused. As a result, all the materials used in this product meet the sustainable aims and requirements. The result of the design plan was given after modification and refining, as shown in Figure 9.



(a) (b) (c)

Figure 8. Three sustainable furniture design sketches designed by a one-piece shape and nested and bracketed top and bottom structures. (**a**) table design sketch; (**b**) chair design sketch; (**c**) tea table design sketch.

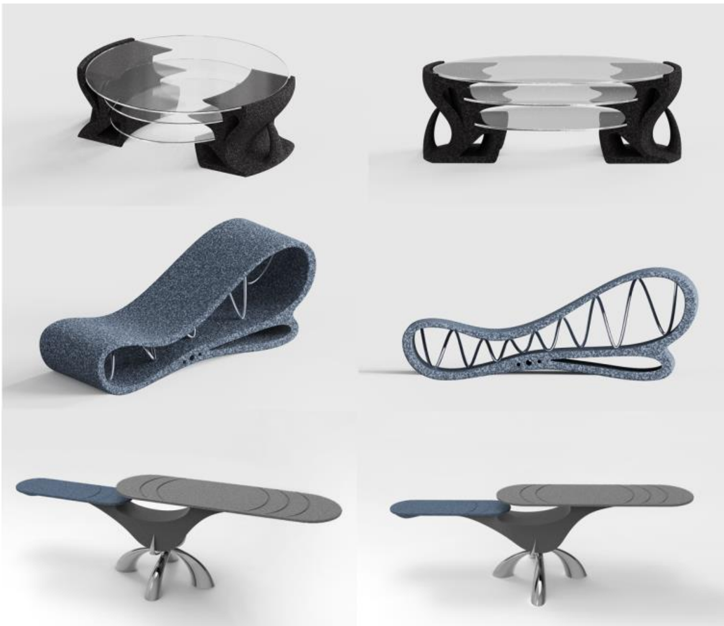


Figure 9. Final renderings of sustainable furniture design. Table based on starch composite integrated molding and glass design (**top**); lying chair (**middle**) and tea table (**bottom**) based on starch composite integrated molding and steel design.

3.3. Discussion

The life cycle of waste textile composite material products can go through several cycles. Maximizing the value of waste textiles and substituting furniture for other materials can successfully limit the use of non-environmental materials while also reducing the exploitation of natural materials such as wood and stone. However, due to the limitations, this study remains insufficient. The composite materials examined in this study cannot be considered eco-sustainable in the strictest sense, because no matter how many times waste textiles are recycled, they must eventually deteriorate. There may be chemical gases and remnant non-degradable fibers produced during breakdown. When utilizing molds to create composites, there is a certain amount of waste. Currently, the ecological recycling path of waste textiles is still being investigated and requires ongoing improvement and refinement based on experience. This material's design technique may have importance and value for sustainable design. However, the path to sustainability requires the continued support and efforts of the government, businesses, society, designers, and the public to advance.

Meanwhile, although there will be some physical and chemical processes for recycling and decomposing waste textiles, it is believed that with the continuous progress of technology, more effective and sustainable treatment methods will emerge. For designers, what they can do is maximize the service life of waste textiles-starch materials and make full use of them. Waste textiles-starch composites can replace some wood, panel, stone, and synthetic materials in furniture, industrial products, and even structures, thus reducing human use of the earth's resources and contributing to ecological sustainability.

4. Conclusions

This study discusses the research of waste textiles reuse based on sustainable design. The research was supplemented by methods and results in the fields of material science, physics, food processing, etc., to check and verify the sustainability and various advantages of waste textile-starch composite materials. For example, based on sustainability and environmental protection, customized composite materials can be provided according to the design requirements by regulating the heating time, starch type, waste textiles type, material composition proportion, and material form. At the same time, the strength of composite materials can also meet the requirements of various design objectives. Therefore, the waste textile-starch composite produced is applied to furniture design. It can not only save the raw material resources of furniture manufacturing but also reduce the waste of resources caused by the waste of furniture. More importantly, it further solves the problem of harmful substance pollution in the process of furniture production. In addition, this study better studies the design and use situation of materials according to their characteristics and better implements the principle of sustainable resource utilization. However, this composite material still needs to be improved in many aspects, and its role is still limited in the face of a large amount of textile waste. However, we believe that with this as the cornerstone and the continuous development of the sustainable concept, more and better solutions will emerge in the future. The establishment of a community with a shared future for humankind is not just a word; it should be engraved in our minds so that we can work together to protect our lovely planet. We will achieve ecological, social, and economic sustainability as soon as possible.

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