Textile and Product Development from End-of-Use Cotton Apparel: A Study to Reclaim Value from Waste

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Abstract: The textile and apparel production and consumption generate a huge amount of solid textile waste. Mechanical recycling is one main method to recycle cotton waste; however, shredding in mechanical recycling shortens fiber length and reduces fiber quality. As a result, the application of mechanically recycled textiles may be limited. This research investigated mechanical methods to recycle post-consumer cotton textile waste and designed and developed second-life products. This study applied research through design methodology and documented step-by-step textile and product development practices to communicate the results. Using the textiles from deconstructed end-of-use garments with a high cotton content (80% or higher), combined with other materials, the researchers developed yarns, and nonwoven, woven, quilted, tufted fabrics. The researchers tested textile properties such as “yarn” tensile strength and elongation, fabric thickness, thermal resistance, air permeability, and stiffness. Using fabrics developed from end-of-use cotton waste, the researchers designed and developed high-value products such as bags, decorative textile, a hat, cell phone and glasses cases, and garments to contribute to the sustainability and circularity of cotton.

Keywords: end-of-use; cotton; textile; product; design; recycle; sustainability; circularity

1. Introduction

The textile and apparel industry is a large industrial sector with 109 million tonnes of global fiber produced in 2020 [1]. In the U.S., consumers purchased a total of more than 17 billion garments (an average of 51.8 garments per person) in 2020 [2]. Compared with 15 years ago, the consumers purchase twice the amount of clothing but keep them half the time [3]. The huge amount of textile and apparel production and consumption and shorter utilization lifetime generate a large quantity of textile and apparel waste after consumers’ use. In 2018, the U.S. generated 17.03 million tons of textile waste, among which 2.51 million tons (14.7%) was recycled, 3.22 million tons (18.9%) was combusted with energy recovery, and 11.3 million tons (66.4%) was landfilled [4].

Textile recycling is the reprocessing method, which includes mechanical, chemical, and thermal routes, of textile waste for use in new textile or non-textile products [5]. Recycling can be classified into downcycling, in which the recycled material is of lower value or quality than the original product, and upcycling, in which the product from the recycled material is of higher value or quality than the original product [5]. Textile fibers can be produced from chemical and thermal recycling methods, which result in commercially recycled textile fiber products. Examples of this include Unifi’s Repreve® recycled polyester fiber from the thermal recycling process, Teijin’s Eco Circle™ and Itochu’s RENU® recycled polyester fiber from the chemical recycling process, and Lenzing’s Refibra™ recycled lyocell fiber from the chemical recycling process [1]. Mechanical recycling shortens the fiber length and lowers fiber quality, which is typically a downcycling process [5,6]. To avoid downcycling, fabrics can only include up to 20–30% of mechanically recycled material so the quality of the fabric is not significantly reduced [6].
Cotton fiber is the second most widely used fiber in textiles with a global production of 26.2 million tonnes and a 24.4% textile fiber market share in 2020 [1]. The large cotton production causes significant amounts of waste. Every year, 11.6 million tonnes of cotton waste is generated worldwide [6]. Recycling cotton textiles is mainly through chemical or mechanical methods [6]. Using the chemical recycling method, the Lenzing Group (Lenzing, Austria) produces lyocell fiber Refibra™ from cotton textile waste and wood [7]. Shredding in mechanical cotton recycling shortens cotton fiber length and reduces fiber quality by decreasing strength and softness, so mechanical recycling is generally applied on pre-consumer cotton textile waste since post-consumer waste has lower quality from wearing [6].

The purpose of this research was to investigate mechanical recycling methods to recycle post-consumer cotton textile waste and design and develop second life products. This research intended to fill the research gap to mechanically recycle post-consumer cotton waste and develop high-value products from these recycled materials. This study applied the research through design methodology and used the prototypes as the carriers of knowledge [8]. The researchers accomplished three objectives in this research: (1) develop textile fabrics from end-of-use cotton apparel products; (2) evaluate properties of textile materials made from end-of-use apparel products; and (3) develop textile products using fabrics made from end-of-use apparel products to contribute to the sustainability and circularity of cotton.

2. Literature Review

2.1. Apparel and Textile Waste

It is estimated that 92 million tonnes of textile waste is generated in the world each year, and it is expected to increase to 134 million tonnes per year by 2030 [9]. There are two types of textile waste: pre-consumer waste that is created in fiber, yarn, fabric, and apparel production before the consumers purchase the product; and post-consumer waste that is formed when consumers dispose the apparel after use at the end of the product’s life cycle [10].


After purchase, each garment is used seven or eight times on average [3]. The lifetime of garment utilization in the UK is 3 years [12]. The shortened life cycle of clothing and the disposal mindset of consumers caused an increase in post-consumer textile waste [13]. In the State of Florida, an average of 101.0 pounds of post-consumer textile waste was generated per person in 2019, which represented a 24.8% increase from an average of 80.9 pounds of post-consumer textile waste generation per person in 2014 [14].

2.2. Textile Waste Management

The waste hierarchy from the most to least preferred waste management methods are waste prevention, preparation for re-use, recycling, energetic recovery, and disposal on a waste dump (landfill) [7]. In the apparel industry, the effort to prevent solid textile waste mainly dealt with the pre-consumer textile waste from the apparel cut-and-sew process. The apparel cutting process results in about 10–15% of cut-and-sew fabric waste due to gaps, non-usable areas between pattern pieces, and curved pattern edges [15]. Design researchers explored creative zero-waste pattern cutting methods so that the pattern completely fits the dimensions of the fabric and uses the entire width and predetermined length of the fabric [16].

When consumers no longer need a garment, they generally sell, give, or donate it so the garment may be re-used by another person. A study in the UK reported that 36% of unwanted clothing was donated to charity shops, about one-quarter was given to family members or friends, about one-fifth was reused in the home, and 7.1% was sold online,
in car boot sales, or second-hand shops [17]. Consumers prefer to donate their unwanted clothing to charity or second-hand stores [18,19]. A study in Edmonton, Canada found that 91% of consumers “always”, “almost always”, or “usually” donate unwanted clothing [19]. Charity organizations sell about 10–20% of donated clothing in their stores, export about two-thirds of donated clothing to developing countries, and send the rest to recycling plants [20]. However, for most second-hand clothing, exporting is just a cheap way to get rid of them [21]. Though the global trade of second-hand clothing grew drastically to a trade value of about $36 billion in 2021, about half of them end up in dumpsites, rivers, or are burnt in the open in the imported countries because there is no market value (e.g., sizes do not fit, not useful due to the local climate, poor quality, broken, or soiled) in these countries [21].

This research focuses on textile recycling. The textile recycling is reviewed in the next section. Energetic recovery and disposal on a waste dump (landfill) are low in the waste hierarchy and are not reviewed. The environmental benefits and impacts of textile waste energy recovery and disposal to landfill can be found in literature [20]. It is estimated that 87% of total textile fiber input is incinerated or landfilled, which results in an annual global opportunity loss of more than 100 billion U.S. dollars [22].

2.3. Textile Recycling

Textile can be recycled through mechanical, thermal, and chemical methods [5]. Mechanical textile recycling involves shredding the fabric into the fibrous forms, which are re-spun into yarns or manufactured into nonwoven textiles [6]. Mechanical recycling is more flexible on fiber content: fabrics made from any fiber type and fiber blend can be shredded and recycled [20]. However, shredding shortens fiber length and reduces fiber quality, so mechanical recycling is generally applied on pre-consumer textile waste, which does not experience wearing and tearing and has higher quality than post-consumer waste [6]. Yarn manufacturer Hilaturas Ferre (Banyeres de Mariola, Spain) shredded pre-consumer cotton textile clips and small amounts of post-consumer garments into fibers of 10 to 15 mm length, which were spun into cotton or cotton blend yarns [23]. About 95% of recovered fibers through shredding or disintegration are processed into nonwovens rather than re-spun into yarns [7]. Researchers shredded acrylic and wool waste to develop needle-punched nonwoven that has a thermal conductivity property comparable with conventional insulation material and can be used for building insulation [24].

Thermal recycling involves converting thermoplastic waste, usually polyester flakes, pellets, or chips, into fibers by the melt extrusion fiber production process [5]. Thermal recycling is the method to produce polyester fibers from recycling polyester plastic bottles. A large quantity of recycled polyester fibers with a big market share are produced from the thermal recycling method. In 2020, the global production of recycled polyester was 8.4 million metric tons, which accounted for 14.7% global polyester production, and about 99% of all recycled polyester are made from polyester plastic bottles [1]. A small percentage of polyester textile fabric is thermally recycled. Unifi Inc. (Greensboro, NC, USA) has a Textile Takeback Program to collect pre-consumer (post-industrial) textile scrap waste from its partner companies and recycle them into Repreve® polyester fibers [25].

There are two routes of chemical recycling: synthetic polymer fibers are depolymerized to monomers and repolymerized to polymer; and natural or regenerated cellulosic textiles are dissolved in solvent and wet-spun into regenerated cellulosic fibers [5]. Mg–Al double oxides were used as the catalyst to depolymerize polyester poly(ethylene terephthalate) (PET) textile waste through a glycolysis process and generated monomer bis(hydroxyethyl) terephthalate (BHET), which were synthesized to PET for recycled polyester fiber production [26]. Teijin Ltd. (Tokyo, Japan) created an “eco circle” program to chemically recycle polyester textiles through the depolymerization and repolymerization process [27]. The recycled polyester made by Teijin has the equivalent quality to the polyester made from petrochemicals [27]. Cotton textile waste was dissolved in solvent such as N-methylmorpholine N-oxide (NMMO) solution and alkali/urea solvent system and wet-spun into regenerated
cellulosic fibers [28,29]. The Lenzing Group (Lenzing, Austria) produces regenerated cellulose lyocell fiber Refibra™ from cotton textile waste and wood using the chemical recycling process [7]. The initial raw materials for Refibra™ lyocell fiber production included 20% pre-consumer cotton waste, which was increased to 30% in 2019 [1].

Thermal and chemical recycling routes require high material purity; therefore, separation is necessary to recycle textiles made from fiber blends. A UK-based company Worn Again developed closed-loop recycling technology that separated and recycled polyester in a blended polyester-cotton textile by using polyester solvents such as aromatic esters, aldehydes, and dipropylene glycol methyl ether acetate at an elevated temperature of 100 °C to dissolve the polyester [30]. The undissolved cellulose was separated through hot filtration, and the polyester was obtained by using isopropanol as an antisolvent and was then recycled [30].

2.4. Products Made from Recycled Textiles

There are many successful commercial textile fibers made from thermal and chemical recycling processes such as Repreve® polyester from Unifi, Refibra™ lyocell from Lenzing, and the Eco Circle™ polyester from Teijin. These recycled fibers are used by textile and apparel companies to produce textile and apparel products including the North Face’s Denali line of fleece jackets and Cone Denim’s Cone Touch™ denim made from Repreve® polyester fibers [25], and apparel brands Patagonia, Reformation, and DL 1961’s product lines made from Refibra™ lyocell fibers [20]. Apparel brands such as Patagonia, Swany America, and Quiksilver in France are members of Teijin’s “eco circle” program and develop products using Teijin’s chemically recycled Eco Circle™ polyester fibers [31]. The shredding and tearing processes in the mechanical recycling shorten the fiber length and reduce fiber quality, which may result in low value products such as rags or insulation materials [32], or the blending of mechanically recycled materials with a high percentage of new materials in fabric production to assure fabric quality [6].

Many research and product development efforts focused on recycling materials other than post-consumer cotton textile waste to develop high-value products. This research intended to investigate mechanical methods to recycle post-consumer cotton textile waste and develop high-value products from these recycled materials.

3. Materials and Methods

3.1. Research through Design Methodology

This study applied the research through design methodology. Research through design is a type of design research that has a designerly inquiry focused on making an artefact with the intended goal of societal change [33]. Research through design uses prototypes as the carriers of knowledge [8] and is about research on the future [33]. There are three types of research through design, i.e., materials research, development work, and action research [34]. Partnerships between designers and scientists are especially useful in materials research [34]. In action research, a research diary of step-by-step practices and a report aiming to contextualize it are used to communicate the results [34]. Research through design methodology was applied by a transdisciplinary collaborative team to design and develop sensorial clothing prototypes that enable the wearer to experience bodily sensations of material substances of a cloud, water, or air, and affect the wearer’s perception of their own body [8]. In this research, textile scientists and fashion and apparel product designers formed a transdisciplinary team. A few fashion and apparel products were designed and developed, and these prototypes serve as the carriers of knowledge. This paper documented step-by-step textile material development and testing and product design and development practices to communicate the results.
3.2. Collection, Sorting and Cutting End-of-Use Textile Products and Fabrics

The researchers collected used apparel products that cannot be sold in Goodwill stores from Goodwill of Delaware and Delaware County (Goodwill DE). After collection, the researchers sorted these products and selected the products that have high (80% or higher) cotton content as the starting materials for the project. The researchers removed non-textile materials, such as zippers and buttons, from the end-of-use garments. In addition to end-of-use apparel, the researchers also used a limited amount of other textile waste (e.g., leftover textile fabrics from school projects and deadstock fabrics) and a very small amount of new textiles (e.g., cotton fibers, yarns and threads) in the textile development.

The researchers used a textile shredder (Taskmaster® Model TM8512, Franklin Miller Inc., Livingston, NJ, USA) to shred a mixture of end-of-use textiles that have more than 80% cotton content. The researchers also hand shredded (hand cut using scissors) textile scraps from end-of-use garments. These textile shreds were used in further textile development.

3.3. Batting Development

The researchers developed batting from textile shreds. The materials used in batting were composed of new cotton sliver, shredded (cutting with scissors or machine shredded) end-of-use cotton garments, and recycled fibers (acquired as a packaging material, fiber content unknown). Fibers were carded together on a Strauch (Hickory, NC, USA) carding machine to develop batting.

3.4. Yarn Development

The researchers explored two methods to develop yarns from end-of-use garments, i.e., pulling the yarns out from an end-of-use knitwear garment and cutting narrow strips from the end-of-use textiles. It is easier to pull out big denier yarns than small denier yarns from knitwear without breaking the yarns. The researchers pulled the yarns out from an end-of-use multi-color cotton sweater to obtain yarns.

The researchers used scissors and a rag cutter (Bliss Model A) to cut the end-of-use textiles to $\frac{1}{4}$ to 1-inch-wide strips that can be used as “yarns” in the weaving or tufting processes. To increase the length of the fabric strips and make “continuous yarns”, the researchers knotted or sewed the fabric strips.

3.5. Fabric Development

Feltloom nonwoven fabrics, woven fabrics, quilted fabrics, and loop-tufted fabrics were developed from end-of-use cotton garments and other textile materials.

3.5.1. Feltloom Nonwoven (Needle-Punched) Fabric Development

The needle-punched nonwoven fabric was developed using a Feltloom (Model Lexi, Feltloom, Sharpsburg, KY, USA). There were two or three layers of materials used in the Feltloom nonwoven development. The ground fabric (bottom layer) was a fabric cut from an end-of-use garment. The middle layer (which is optional and can be skipped) was recycled textile fiberweb (acquired as a packaging material, fiber content unknown). There were two types of top layer material: (a) the batting material (the development process was described in the previous section); and (b) shredded end-of-use textile waste. Figure 1 shows a 3-layer felting process using hand-cut textile shreds as the top layer.
3.5.2. Woven Fabric Development

The woven fabrics were developed by two methods, i.e., using a Macomber Add-a-harness floor loom (Macomber Looms, York, ME, USA) (Figure 2a) and a frame loom (Figure 2b). The Macomber floor loom was used to develop wider fabric. In the Macomber floor loom production, the warp yarn consisted of Perle Cotton 10/2, Nautical Blue, purchased from the Woolery (woolery.com, accessed on 26 April 2022). The weft/fill “yarn” consisted of 100% cotton narrow textile strips cut from 100% cotton end-of-use garments. The frame loom, which was used to produce narrow and small-size woven fabrics, was made from cardboard and tape. During the weaving process of the frame loom, the warp yarn used was 100% new cotton yarn (white color), and the filling yarn the ribbon-cut end-of-use cotton apparel.

3.5.3. Quilted (Confetti Quilting) Fabric Development

Figure 3 shows the confetti quilting process, which was undertaken by shreds from 100% cotton end-of-use garments. There were two ways to develop confetti-quilting fabric: with a big piece of fabric as a base or without a big piece of fabric as a base. When a base fabric was used, the shredded small pieces of fabric were placed on top of a big piece of cotton woven fabric cut from an end-of-use shirt or a 100% cotton muslin fabric waste (leftover fabric from school projects) (Figure 3a), and then covered with Solvy (Water Soluble Stabilizer). When a base fabric was not used, shredded fabric scraps were
layered between two layers of Solvy and pinned. The researchers used a free-form embroidery technique to quilt the fabric with 100% Dual Duty cotton thread and an embroidery presser foot on a Singer professional home machine. Figure 3b shows quilting with a base fabric, and Figure 3c shows quilting without a base fabric. Upon completion of the free-form embroidery process, the fabric was hand laundered in warm water to remove the Solvy substrate.

Figure 3. Confetti quilting process ((a): small fabric shreds were placed on top of a base fabric; (b) confetti quilting process with a base fabric; (c): confetti quilting process without a base fabric).

3.5.4. Loop Tufted Fabric Development

End-of-use garments were cut into $\frac{3}{4}$-inch strips that were used as tufting yarns. The tip of each strip was inserted into the tufting machine with a metal hook. The operation involved tufting in vertical lines of 18 inches into a 100% cotton open-weave cloth, supported by an 18-inch $\times$ 18-inch wooden frame. Sample fabrics were cut to size and secured with a zigzag stitch using 100% cotton Dual Duty thread, sewn on a Singer professional home sewing machine. The back of the tufting sample was glued, and a 100% cotton muslin cloth (leftover textile fabrics from school projects) was applied. The loop tufting process is shown in Figure 4.

Figure 4. Loop tufting process ((a): loop pile tufting machine from Tuft the World (tuftinggun.com, accessed on 26 April 2022); (b): tufting process).
3.6. Textile Testing

Before yarn and fabric testing, except for the thermal resistance (R<sub>ct</sub>) testing, all samples were conditioned at 21 °C and 65% relative humidity in an Environmental Chamber (Lunaire, Model No. CE0910-4, Thermal Product Solutions, New Columbia, PA, USA) in accordance with ASTM D1776 method (Standard Practice Conditioning and Textile Testing).

3.6.1. Yarn Testing

The researchers tested the tex (g/km), tensile strength, and elongation of the yarns to evaluate whether it can be woven or knitted into textile products. To measure the tex data, the researchers measured the weight of 16 inches of the yarn (with three replications) and converted the results to g/km (tex).

The tensile strength and elongation were measured in accordance with ASTM D2256 (Standard Test Method for Tensile Properties of Yarns by the Single Strand Method) using a H5KT Benchtop Materials Tester (Tinius Olsen, Horsham, PA, USA). There were three replications of tensile strength and elongation test for each specimen.

3.6.2. Fabric Testing

For the fabric samples, the researchers measured thickness, thermal resistance (R<sub>ct</sub>), stiffness/softness, and air permeability. The thickness was measured using a portable gauge (SDL Atlas, Rock Hill, SC, USA). There were ten replications for each test.

R<sub>ct</sub> data were measured by a sweating, guarded hotplate (Thermetrics, Seattle, WA, USA) in accordance with ASTM F1868 standard (Standard Test Method for Thermal and Evaporative Resistance of Clothing Materials Using a Sweating Hot Plate). There were three replications for each test.

The stiffness/softness data were measured using a Handle-o-meter (Thwing-Albert Instrument Co., West Berlin, NJ, USA) in accordance with ASTM D6828 standard (Standard Test Method for Stiffness of Fabric by Blade/Slot Procedure). In the test, the slot width was set at 20 mm and a 1000 g beam was used. Each sample was tested in four different directions to calculate the average for one sample.

The researchers measured air permeability data using an Automatic Air Permeability Tester (Model AG18B, Aveno Technology Co., Quanzhou, China) in accordance with ASTM D737 standard (Standard Test Method for Air Permeability of Textile Fabrics). The sample area in the test was 20 cm<sup>2</sup>. There were ten replications for each air permeability test.

3.7. Product Development

3.7.1. Cell Phone Cases and Glasses Case

For the cell phone case prototypes, the textile fabrics were developed by two methods, i.e., confetti quilting and the Feltloom needle-punched process, as described in the previous section. The fabrics (Figure 5) were cut into rectangles and sewn with a Singer Heavy Duty Sewing machine with a white, dual-duty cotton thread to make cell phone cases. A woven fabric made from the Macomber floor loom was used for the glasses case prototype development.
The nonwoven fabrics were cut into two rectangles for the body of the bag and two square and X shape to secure it, and then sewed the pocket onto the plaid side of the bag. Then, the researcher stitched the top of the bag and the straps (Figure 7b). The bottom of the right and left corner of the rectangles were cut out to make the body of the bag. Then, the researcher sewed the side seams and bottom seam of the bag, and sewed the squares on the bottom of the bag to give it dimension.

3.7.2. Decorative Fabric

End-of-use cotton products with different colors were cut into narrow strips (as in Figure 6a) and were tufted on an end-of-use cotton fabric. Figure 6b shows the tufting process.

3.7.3. Bags: Handbag, Backpack, Makeup Bags, Tote Bag

Nonwoven fabric (Figure 7a) made from the Feltloom was used to make the handbag. The nonwoven fabrics were cut into two rectangles for the body of the bag and two rectangles for the straps of the bag, and two pockets. Two squares of 1 ¼” by 1 ¼” in the bottom of the right and left corner of the rectangles were cut out to make the body of the bag. Then, the researcher stitched the top of the bag and the straps (Figure 7b). The researcher sewed the straps onto the two rectangles that make up the body of the bag in a square and X shape to secure it, and then sewed the pocket onto the plaid side of the bag (Figure 7c). Lastly, the researcher sewed the side seams and bottom seam of the bag, and then sewed the squares on the bottom of the bag to give it dimension.
4.1. Textile (Batting, Yarn, Fabrics) Development

4.1.1. Batting Material

The batting material is shown in Figure 8. It would serve as the intermediate material for Feltloom nonwoven development.

3.7.4. Hat

Batting was made from machine-shredded fabric from end-of-use cotton apparel. The batting was sent through the Feltloom machine 10 times in all four directions to produce a needle-punched nonwoven textile. The nonwoven textile was cut into a circle and a rectangle. The rectangle was gathered to create fullness and sewn together with the circle fabric using a Singer Heavy Duty Sewing machine with white Dual Duty cotton thread.

3.7.5. Garments

End-of-use cotton products (with different colors) were cut into narrow strips. The narrow strips were tufted on a cotton monk cloth. The tufted textile was hemmed with an ⅜ inch hem with cotton Dual Duty thread and attached to a denim jacket (end-of-use jacket obtained from Goodwill DE) by hand tacking with thread.

A moto jacket was developed from a flat pattern method applying needle-punched Feltloom fabric (made by shredded end-of-use cotton apparel products and new cotton sliver) for the front and back bodice. The lapels and collar were toplined with a different needle-punched Feltloom fabric. The sleeves were cut from end-of-use cotton leggings. The jacket was sewn on a Juki industrial sewing machine (model DDL-87) with white Dual Duty cotton thread. The jacket has no closures.

4. Results and Discussion

4.1. Textile (Batting, Yarn, Fabrics) Development
4.1.2. Yarn

The narrow fabric strips cut from end-of-use garments that can be used as yarns are shown in Figure 9.

4.1.3. Feltloom Nonwoven Fabric

A few needle-punched nonwoven fabric samples made with the Feltloom are shown in Figure 10. The top layer of the sample in Figure 10a is the batting material. The top layer of samples in Figure 10b–d are shredded textiles from end-of-use garments (hand cut using scissors for Figure 10b,c and a textile shredder machine for Figure 10d.)
4.1.4. Woven Textile

Woven fabrics made from Macomber floor loom or frame loom are shown in Figure 11.

4.1.5. Quilt Fabric

Confetti quilting textile fabrics are shown in Figure 12. Figure 12a shows the confetti-quilted fabrics without a base fabric (only shredded end-of-use garment scraps were used). Without a base fabric, some pieces of small fabric scraps may not be sewn and may have holes. This would create a lace-like fabric, but its strength may be compromised. Figure 12b–d show the confetti quilted fabrics with a base fabric. These would be more stable and stronger fabrics. The shredded fabrics in Figure 12b,c were hand shredded with scissors, and in Figure 12d, they were shredded from a textile shredder machine.

Figure 10. Needle-punched nonwoven fabrics made from a Feltloom ((a): Feltloom nonwoven fabric with batting material as the top layer; (b): Feltloom nonwoven fabric with hand cut fabric shreds as the top layer, sample 1; (c): Feltloom nonwoven fabric with hand cut fabric shreds as the top layer, sample 2; (d): Feltloom nonwoven fabric with machine cut fabric shreds as the top layer).

Figure 11. Woven fabrics made from loom ((a): woven fabric sample 1; (b): woven fabric sample 2).

Figure 12. Confetti quilting textile fabrics are shown in Figure 12. Figure 12a shows the confetti-quilted fabrics without a base fabric (only shredded end-of-use garment scraps were used). Without a base fabric, some pieces of small fabric scraps may not be sewn and may have holes. This would create a lace-like fabric, but its strength may be compromised. Figure 12b–d show the confetti quilted fabrics with a base fabric. These would be more stable and stronger fabrics. The shredded fabrics in Figure 12b,c were hand shredded with scissors, and in Figure 12d, they were shredded from a textile shredder machine.
4.1.6. Tufting

Loop tufted textile samples are shown in Figure 13. Fabric strips of ¼ inch width were used as the tufting “yarns”. Fabric strips with different colors can be used to make tufting color patterns.

4.2. Textile Testing

4.2.1. Yarn Testing

The researchers tested the strength and elongation of two types of “yarns”: yarns pulled out from an end-of-use multi-color cotton sweater that contains three yarns, i.e., green, grey, and white, and ¼ inch fabric strips cut from an end-of-use woven cotton fabric using a Rag Cutter. The tensile properties of the yarns are shown in Table 1. For comparison, one research study reported that the 184 different “new” cotton yarns’ (size 12 tex or 27 tex) tenacity was in the range of 57 mN/tex to 174 mN/tex (0.646 gf/denier to 1.971 gf/denier) [35]. The tenacity of yarns pulled out from end-of-use cotton garments are comparable to the tenacity of “new” cotton yarns. This indicated the wear and care of the used sweater, and the process to pull yarns out of the sweater did not significantly weaken the yarns. Yarns pulled out from end-of-use sweaters can be re-used in textile development.

The size (tex number) of the ¼-inch cotton fabric strip was much larger than the machine-spun yarn. In literature [35], the yarns for both the lowest tenacity (57 mN/tex) and the highest tenacity (174 mN/tex) have the diameter of 27 tex. The ¼-inch cotton fabric strip has a tenacity of 0.27 gf/denier, which is smaller than the lowest tenacity (57 mN/tex or 0.646 gf/denier) reported in literature [35]. The low tenacity is caused...
by the much bigger size (1443 tex of \( \frac{1}{4}\)-inch cotton fabric strips vs. 27 tex in [34]). The breaking force of the highest tenacity (174 mN/tex) in literature [35] was 4.698 N (or 4698 mN = 174 mN/tex \times 27 tex), which was 0.48 kgf. The \( \frac{1}{4}\)-inch cotton woven strips’ breaking force of 3.535 kgf is much higher than the 0.48 kgf breaking force in literature [35]. The high breaking force will ensure the \( \frac{1}{4}\)-inch cotton woven strips will not be broken in future weaving, knitting, or other fabrication (e.g., tufting) processes, and can be used as “yarns” in these processes.

**Table 1.** Tenacity and Elongation of yarns pulled out from an end-of-use sweater.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Tex</th>
<th>Breaking Force (kgf) Mean ± SD</th>
<th>Tenacity (gf/denier) Mean ± SD</th>
<th>Elongation (%) Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green yarn pulled from an end-of-use knitwear</td>
<td>73</td>
<td>1.173 ± 0.060</td>
<td>1.785 ± 0.092</td>
<td>12.79 ± 0.33</td>
</tr>
<tr>
<td>Grey yarn pulled from an end-of-use knitwear</td>
<td>49</td>
<td>0.406 ± 0.029</td>
<td>0.921 ± 0.067</td>
<td>11.85 ± 1.63</td>
</tr>
<tr>
<td>White yarn pulled from an end-of-use knitwear</td>
<td>122</td>
<td>0.923 ± 0.106</td>
<td>0.840 ± 0.097</td>
<td>16.39 ± 1.50</td>
</tr>
<tr>
<td>( \frac{1}{4})-inch wide woven fabric strip</td>
<td>1443</td>
<td>3.535 ± 0.730</td>
<td>0.272 ± 0.056</td>
<td>23.48 ± 0.94</td>
</tr>
</tbody>
</table>

### 4.2.2. Fabric Testing

The researchers measured the thickness, thermal resistance \( R_{ct} \), stiffness of two Feltloom nonwoven samples (Feltloom sample 1: Figure 10b, Feltloom sample 2: Figure 10c), one woven sample (Figure 11b), one confetti quilt sample (Figure 12c), one tufting sample (Figure 13c). The results are in Table 2. The air permeability data of all of these samples indicate that these fabrics are breathable and can meet the breathability comfort requirement for wearable products. Three layers of materials were used in the production of Feltloom nonwoven fabrics, which resulted in thick fabrics. Narrow fabrics cut from end-of-use garments were used as “yarns” in the development of woven fabrics. These “yarns” are much bigger (higher tex) than regular yarns. So, the woven fabric samples are also thick. Due to the higher thickness, the fabrics made from Feltloom and loom weaving have high thermal resistance and are stiff. These fabrics are appropriate for products that require high thickness and stiffness such as bags and decorative fabrics, and products that provide warmth (require high thermal resistance) such as blankets and winter apparel. The confetti-quilted fabric is the thinnest, softest, and has the lowest thermal resistance among the five samples. It can be used in apparel products for spring and fall seasons, and to make bags and decorative textile products.

**Table 2.** Fabric thickness, thermal resistance, stiffness, air permeability test results.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Thickness (Mean ± SD) (mm)</th>
<th>( R_{ct} ) (Mean ± SD) °C m²/W</th>
<th>Stiffness (Mean ± SD) (g)</th>
<th>Air permeability (Mean ± SD) (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feltloom sample 1</td>
<td>3.04 ± 0.28</td>
<td>0.0797 ± 0.0025</td>
<td>122.45 ± 3.76</td>
<td>423.01 ± 30.71</td>
</tr>
<tr>
<td>Feltloom sample 2</td>
<td>3.32 ± 0.44</td>
<td>0.1080 ± 0.0003</td>
<td>319.70 ± 20.15</td>
<td>333.98 ± 52.18</td>
</tr>
<tr>
<td>Woven</td>
<td>3.96 ± 0.51</td>
<td>0.0937 ± 0.0011</td>
<td>230.10 ± 3.54</td>
<td>694.99 ± 95.69</td>
</tr>
<tr>
<td>Confetti quilt</td>
<td>2.34 ± 0.19</td>
<td>0.0430 ± 0.0009</td>
<td>77.75 ± 8.58</td>
<td>409.79 ± 41.60</td>
</tr>
<tr>
<td>Tufting</td>
<td>8.58 ± 0.39</td>
<td>0.0892 ± 0.0034</td>
<td>&gt;1000</td>
<td>313.38 ± 61.29</td>
</tr>
</tbody>
</table>

In addition, the researcher measured the thickness of two loop tufted textile samples (Figure 13a,b). Their thickness data are 7.816 mm (SD = 0.747) and 8.535 mm (SD = 0.419), respectively. Their stiffness data are higher than 1000 g (out of the 1000 g test range of the Handle-O-Meter). These loop tufted fabrics are very thick and stiff. They can be used for rugs and decorative textiles. In apparel products, the loop tufting fabric cannot be used in the areas that require bending and flexibility, e.g., elbow and knee areas.
4.3. Product Development

4.3.1. Cell Phone Cases and Glasses Case

Two cell phone case prototypes were developed using confetti fabric and feltloom needle-punched fabric, respectively. One glasses case prototype was developed using woven fabric made from end-of-use cotton apparel. They are shown in Figure 14.

![Figure 14](image1)

Figure 14. Cellphone case and glasses case prototypes ((a): confetti quilt cell phone case; (b): feltloom fabric cell phone case; (c): glasses case).

4.3.2. Decorative Fabric

The decorative fabric made from the tufting process using end-of-use cotton strips as tufting “yarns” is in Figure 15.

![Figure 15](image2)

Figure 15. Decorative tufting fabric made from end-of-use cotton products.

4.3.3. Bags: Handbag, Backpack, Makeup Bag, Tote Bag

The handbag, backpack, makeup bag, and tote bag prototypes developed by the researcher are in Figure 16. Figure 16a–c show bag prototypes made from different types of feltloom nonwoven fabrics. Figure 16d,e is a tote bag prototype (two sides) made from woven fabric using narrow fabric strips as filling “yarns”.

![Figure 16](image3)
4.3.4. Hat

The hat prototype developed from needle-punched feltloom fabric (made by shredded end-of-use cotton apparel products and new cotton sliver) is shown in Figure 17.

![Hat prototypes](image)

Figure 16. Bag prototypes ((a): handbag; (b): backpack; (c): makeup bag; (d) and (e): tote bag).

4.3.5. Garments

The jacket made from tufted textile (made from end-of-use cotton products) and an end-of-use denim jacket (cannot be sold in Goodwill DE and was acquired by the researchers from Goodwill DE) is shown in Figure 18.

![Garments](image)

Figure 17. Hat prototype ((a): side view; (b): back view).

Figure 18. Garments (a): jacket made from tufted textile; (b): end-of-use denim jacket.
4.3.5. Garments

The jacket made from tufted textile (made from end-of-use denim jacket and an end-of-use pair of leggings (acquired by the researchers from Goodwill DE) is shown in Figure 19.

Figure 18. Jacket made from tufted cotton fabric and an end-of-use denim jacket ((a): jacket with tufted textile; (b): details of tufted textile).

The jacket made from two Feltloom nonwoven textiles (made from machine-shredded, end-of-use cotton garments) and an end-of-use pair of leggings (acquired by the researchers from Goodwill DE) is shown in Figure 19.

Figure 19. Jacket made from felted cotton fabric ((a): front; (b): back).

5. Conclusions

This research investigated mechanical recycling methods to recycle post-consumer cotton textile waste and designed and developed high-value, second-life products. The researchers developed and tested a variety of yarns and fabrics from end-of-use cotton apparel products. Using these fabrics, apparel, accessories, and decorative textile products were developed. This study applied research through design methodology and documented step-by-step textile material development, and we used testing and product design and development practices to communicate the results [34]. The prototypes served as the carriers of knowledge [8].

Mechanical recycling is one of the main methods to recycle pre-consumer cotton textile waste [6]. The shredding and tearing process in the mechanical recycling shortens the
fiber length and reduces fiber quality, so it is a downcycling process to produce low-value products such as rags or insulation materials [32], or the mechanically recycled textiles need to be blended with a high percentage of new fibers in high-quality fabric production [6]. This research explored different mechanical recycling methods to recycle post-consumer cotton waste and developed high-value products including bags, a hat, garments, cell phone and glasses cases, and decorative textiles from the recycled materials. This research provided viable methods to reclaim the value of end-of-use cotton apparel products through mechanical recycling processes. Considering cotton accounts for 24.4% of all textile fibers used [1], there are a huge amount of end-of-use cotton products that become solid waste annually. This research offered solutions to develop valuable products from end-of-use cotton products and contributed to the sustainability and circularity of cotton. This research has the potential to be extended to develop products using end-of-use textiles made from other fibers.

Many stakeholders play roles in the circular fashion business. They are internal stakeholders that include fashion suppliers (e.g., fiber, yarn, and fabric suppliers), retailers (e.g., fashion brands and retailers), clothing manufacturers, product designers (e.g., fabric designers and fashion designers), and external stakeholders that include consumers, academic institutions (e.g., material researchers, design schools), governments, recycling agents (e.g., clothing recycling agents, charities), and investors [36]. This research has the potential to benefit various stakeholders in the cotton textile and apparel industry to contribute to the circular cotton fashion business as summarized in Table 3.

<table>
<thead>
<tr>
<th>Stakeholders</th>
<th>Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fashion suppliers</td>
<td>Access more recycled materials for yarn and fabric production. May produce and sell high value yarns and fabrics made from recycled textiles.</td>
</tr>
<tr>
<td>Retailers</td>
<td>May offer more high-value product lines that are made from recycled textiles.</td>
</tr>
<tr>
<td>Clothing manufacturers</td>
<td>Access more high-value yarns and fabrics for manufacturing. Produce high-value apparel and other textile products from recycled textiles.</td>
</tr>
<tr>
<td>Consumers</td>
<td>Have more high-value product choices made from recycled textiles. If their clothing donations cannot be sold by charities, the end-of-use garments may be recycled and produced into high-value, second-life products.</td>
</tr>
<tr>
<td>Academic institutions</td>
<td>Following the research through design methodology used in this research, material researchers and product designers may work together to design and develop more high-value products from recycled materials.</td>
</tr>
<tr>
<td>Recycling agents</td>
<td>If donated clothing cannot be sold by charities, charities and textile recyclers can work together to recycle end-of-use apparel and produce high-value yarns and fabrics for product development.</td>
</tr>
</tbody>
</table>

A limitation of this study is the prototypes developed from this research have not been evaluated. In the future, the researchers plan to conduct surveys, focus groups, and wearing tests to evaluate the consumer acceptance and willingness to buy the products made from end-of-use textile products.

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