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ORIGINAL PAPER

Cotton Weaving Waste Incorporation in PVC Composites

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Abstract

The largest amount of solid waste from the textile industries is mainly derived from fabric manufacturing until the cutting stage: hard fibers (spinning waste), beaming and soft fibers (weaving yarn waste), and off-cuts (cutting process). This research aimed to (i) conduct an exploratory interview with a large Brazilian cotton textile manufacturer to identify its main solid waste and corresponding destinations; and (ii) produce and evaluate PVC composites reinforced with cotton textile residues from the weaving process. Cotton fibrous reinforcements in the proportion of 2.5% (w/w) presented the best results of tensile strength and elongation concerning the others. Briquette residue (2.5%) had better dispersion in the matrix and slightly higher tensile strength when compared to other residues. The composites presented different visual aspects, and their use in fashion products with sustainable appeal could be a viable alternative. Therefore, additional tests should be performed to ensure the appropriate mechanical properties for applications in this and other areas.

Keywords Textile waste · Cotton weaving residues · PVC · Composite

Introduction

A large volume of solid waste is generated from textile industries in the stages of fiber extraction (cleaning), spinning (yarn), weaving (fabric), and cutting processes for garment manufacturing. During the preparation for weaving, the winding process transfers yarns from a small reel to a big bobbin to warp, it is important in removing defects in the yarn (thick, thin, or nep), which generates wastes (Gandhi 2020). In the weaving process, warp yarns are raised to insert the weft yarns, according to the required design; at this stage, sources of hard waste are break of yarns (weft and warp), bobbin change, or set change (Goyal 2021).

Despite leftovers being a regular part of the weaving process, they can generate waste due to poor creation planning (modeling, cutting, and fitting), quality problems or lack of standardization of raw materials, unqualified labor, inappropriate machines, and among other factors. The sizes, shapes, and volumes of these leftovers vary according to the shapes of the molds, the widths of the fabric rolls, and the correct use of them (Patnaik and Tshifularo 2021; Tutia et al. 2017).

Cotton is the second most-produced fiber in the world, after polyester (Abrapa, 2020). Around 35 million hectares of cotton are cultivated throughout Brazil, in the harvest of 2020/21, the cotton production was 2.6 million tons of fiber, which 2.0 million tons are mainly exported to East (China, South Korea, Indonesia, Pakistan, Thailand, and Vietnam) (CONAB, 2021). In addition to exportation, cotton fiber is processed in the Brazilian textile chain, being the most employed in the national production of fabrics, driven by the production of jeans and knits (T-shirts) (ABIT 2020).

Since the growing consumption of synthetic fibers reinforced composites and the growing concern for the environment, materials that use waste or renewable natural resources could bring ecological and economic benefits (Pereira et al. 2015). The mechanical and thermal properties of composites

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are affected by processing and also by the temperature at which they were made, in addition to depending on the type, shape, and amount of fiber used (Khan et al. 2018).

Polymers are widely employed in various engineering applications, and sometimes, their properties are not sufficient for all requirements. For this reason, polymeric structures are reinforced by fibers to form composite structures. The mechanical and thermal properties of fiber-reinforced composite structures depend on the amount, orientation, and length of the fibers in the structure (Taşdemır and Gülsoy 2008). The uses of vegetable fibers confer a renewable aspect, in addition to being ecological as it adds value to a residue from an industry with large productions. Vegetable fibers when applied correctly propose to produce a material in which the fibers and matrix have good adhesion, made possible to obtain similar mechanical properties or even better than the pure polymer matrix (Pereira et al. 2015; Petrucci et al. 2015). The issue of natural fiber reinforcement polymers is being researched in several applications: thin films (Thitiwongsawet et al. 2017), green vulcanized thermoplastic elastomer (Paran et al. 2019), automotive engineering plastics (Nayak et al. 2018; Sah et al. 2017), and, the most widely studied, wood-plastic composites (Bootkul et al. 2017; Pulngern et al. 2016).

Poly (vinyl chloride) (PVC) is a commodity in the plastics segment, widely used in the industry, due to the great versatility of formulation, low price, and mechanical properties of the material, such as resistance to abrasion (Wu et al. 2016). The flexible PVC formulation is widely applied to the development of thin films for food packaging, hoses, shoe soles, straps, etc. (Thitiwongsawet et al. 2017). Polymeric composites reinforced with natural fibers are increasingly being used in many engineering applications with an extremely wide range of properties (Lotfi et al. 2019).

Thus, the main objectives of this study were as follows: (i) to interview one of the largest Brazilian textile companies to identify its main solid waste and corresponding destinations, with special emphasis on waste arising from the weaving process; (ii) produce and evaluate PVC composites mechanical behavior with reinforcement of cotton textile residues from its weaving process as a way to add value to these textile residues.

Materials and Methods

Cedro Têxtil Interview

The Cedro Têxtil company is one of the main Brazilian textile industries, 100% of national capital employed, and production capacity is 168 million square meters per year. There are 4 factories in Minas Gerais state (Brazilian Southwest), which employs 3 thousand people (Cedro Têxtil 2022).

Denim, twill, and canvas are the major developed fabrics, which are destined to fashion (paints, jacket, shorts — Fig. 1a), professional (painter, apiarist), and technical areas (security, hospital, electrician) (https://www.cedro.com.br/Institucional/Institucional). Thus, the company manufacture fabrics and add special finishing additives, as AM-V — antimicrobial finishing launched in 2020 (Fig. 1b) that acts actively for at least 30 washes; it was tested by the Institute of Biomedical Sciences of the University of São Paulo (USP) and follows the ISO18184 standards for the evaluation of viral activity, including against SARS-COV-2, besides bacteria (*Staphylococcus*, *Escherichia*, *Klebsiella*) and fungus (*Candida albicans*) (Textília.net 2020).

The exploratory interview was carried out by e-mail on 23 March and 26 August of 2021, with the cotton supply manager. The questions focused on solid waste identification and corresponding destinations, with special emphasis on waste from the weaving process. Some cotton residues were donated by Cedro to study them for polymer composite application. It is important to note that all information provided, including the disclosure of the name, was fully authorized by the company.

Fig. 1 Fabric products manufactured by Cedro Têxtil: **a** denim fabric and colors, **b** AM-V — antimicrobial, a finishing additive applied to own fabrics (Cedro Jeanswear 2020)

Composite Development

Crystal PVC (55 IF) matrix was used in a granular format and flexible polymer formulation (Fig. 2a), which was provided by Karina Plastic Industry (Guarulhos-SP, Brazil).

Textile cotton waste from different stages of processing in the weaving industry (Cedro Indústria Têxtil) is constituted by five forms:

- Briquette: obtained from powder generated during the weaving process and cotton fibers (Fig. 2b);
- Raw starched yarn: starched (from warp yarns, from weave preparation) and unbleached cotton yarns (Fig. 2c);
- Selvedge: fabric sideband (named selvedge) removed tostandardize fabric (Fig. 2d);
- Indian starched yarn: starched cotton yarn dyed with indigo (Fig. 2e);
- Post-consumption: obtained from cotton sheets used domestically for 10 years (Fig. 2f).

Processing of PVC Compounds/Textile Waste and Characterization

All cotton residues (except briquette) were cut in guillotine equipment (paper cutting machine) to obtain regular fibrous segments of about 10 mm in length. These materials were incorporated in the proportion of 2.5 and 5.0% of PVC compound (w/w). The final material was blended with two roll mills heated to 150 and 160 °C respectively. After process mixing, the material was molded in hydro-pneumatic press (Fig. 3), at 150 bar, 150 °C for 3 min, to obtain regular boards, with dimensions of 20 × 20 cm and thickness of 3.5 mm. In the same process, the press machine achieved room temperature to cool them and also compressed them at 150 bar for 3 min.

After mixed and molded, plates of composites were cut to produce the specimens (22-mm length, 6-mm width) for mechanical tensile tests, according to the ASTM D412 standard — Standard Test Methods for Vulcanized Rubber and Thermoplastic Elastomers Tension (ASTM International, 2016). Tensile tests (rupture load, elongation, strength, and Young's modulus) were conducted at Instron tester machine (model 5569, Norwood, USA), crosshead speed of 20 mm/min and a cell of 1 kN (texturized grips with dimensions of 2.5 × 2.5 cm) and the distance between the grips of 20 mm.

The thickness of samples was previously determined by employing a portable analogical thickness gage (model 188F, Mesdan, Italy). The results were measured according to the average from at least 6 samples.

Shore A hardness test is applied to composite sheets, through portable equipment from Novotest brand and model TEC-017. In this test, the durometer measures the penetration resistance through an indenter, in which a perpendicular force is applied to the surface of the material. A readout system converts the vertical displacement of the indenter into a Shore hardness value on a suitable scale, which ranges from 0 to 100 Shore. For each sample, three indentations were performed, following the least distance from the margin (13 mm) and between each point analysis (5 mm).

Scanning electron micrographs of the PVC/cotton residues composites were examined on a JEOL JSM-6610 L20, Japan. The surfaces of samples for SEM characterization were first fractured in liquid nitrogen and, sputter-coated with a thin layer of gold before observation.

Results and Discussion

Waste from the Cotton Chain

The production of residues in the cotton chain worldwide is shown in Fig. 4, in which the largest volume produced comes from the separation of fibers from the seed. In preparation for spinning, the bales are opened, mixed, cleaned, and carded. In the carding process, studies have shown that 4.7% of the material is separated as waste, which around 60% of the fiber has the potential to be recovered. Then, in the drawing process, the sliver is mixed, straightened, and the density is adjusted to the desired lap level. In the combing process, the resulting yarn is thinner and generates about

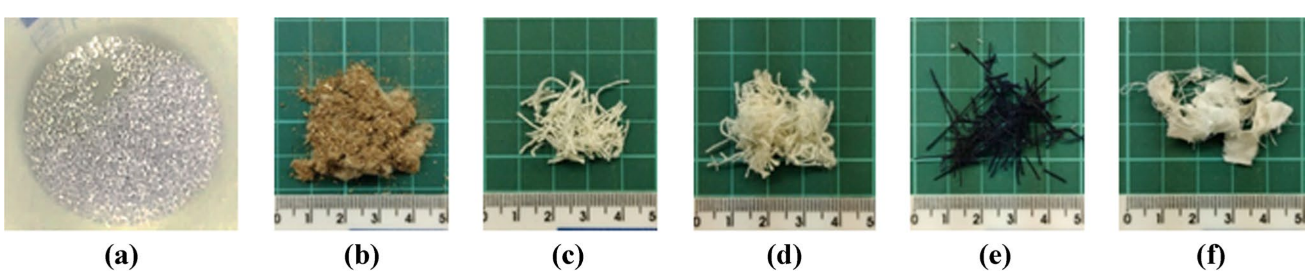


Fig. 2 **a** Granular compound, PVC crystal matrix from Karina Plastic Industry; range of textile waste fibers applied to composites: **b** Briquette; **c** raw starched yarn; **d** selvedge; **e** Indian starched yarn; **f** post-consumption sheet

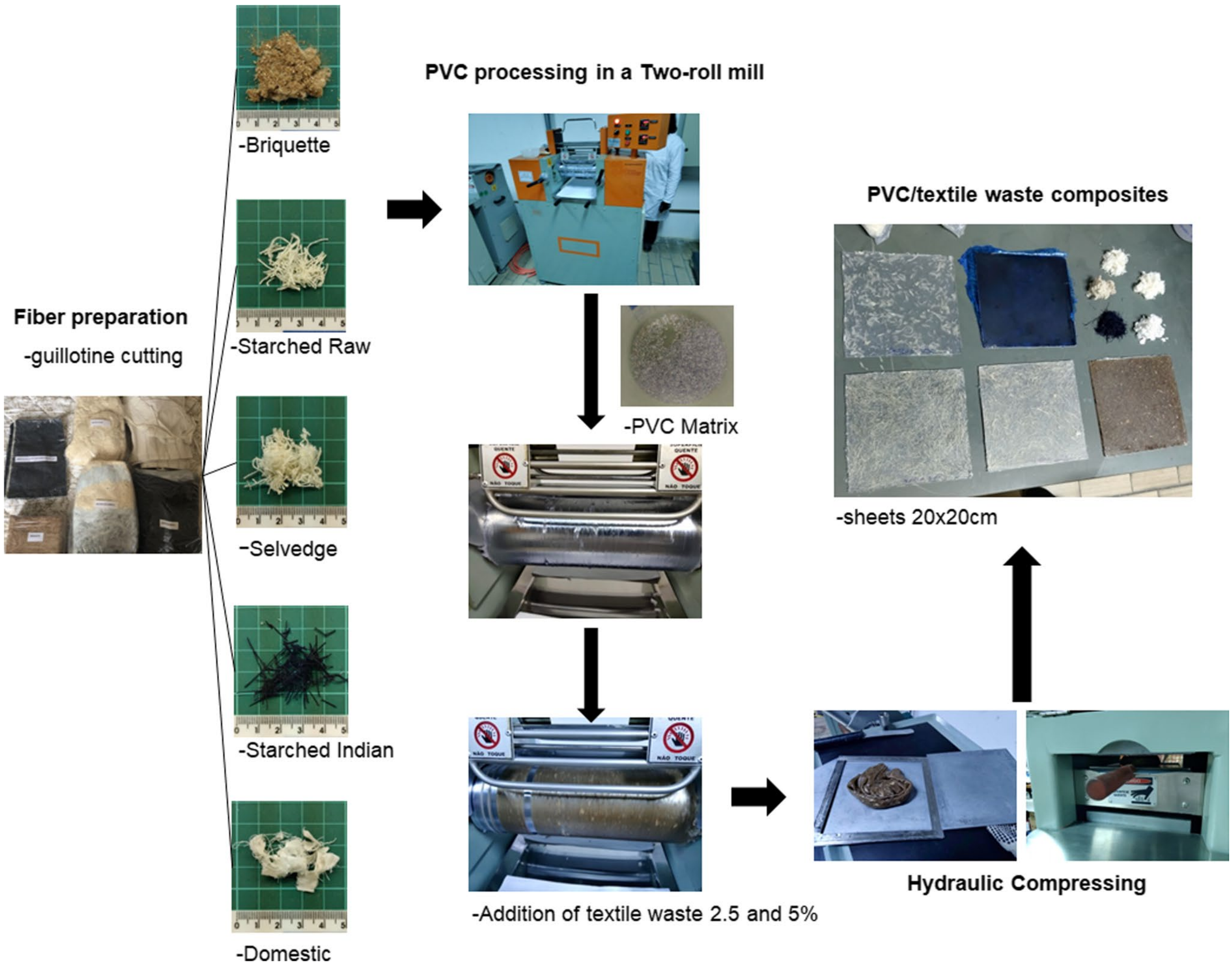


Fig. 3 Schematic processing of cotton wastes and PVC matrix. From left to right: raw waste materials; PVC processing in a two-roll mill; hydraulic compressing; obtained composites. Source: Authors (2021)

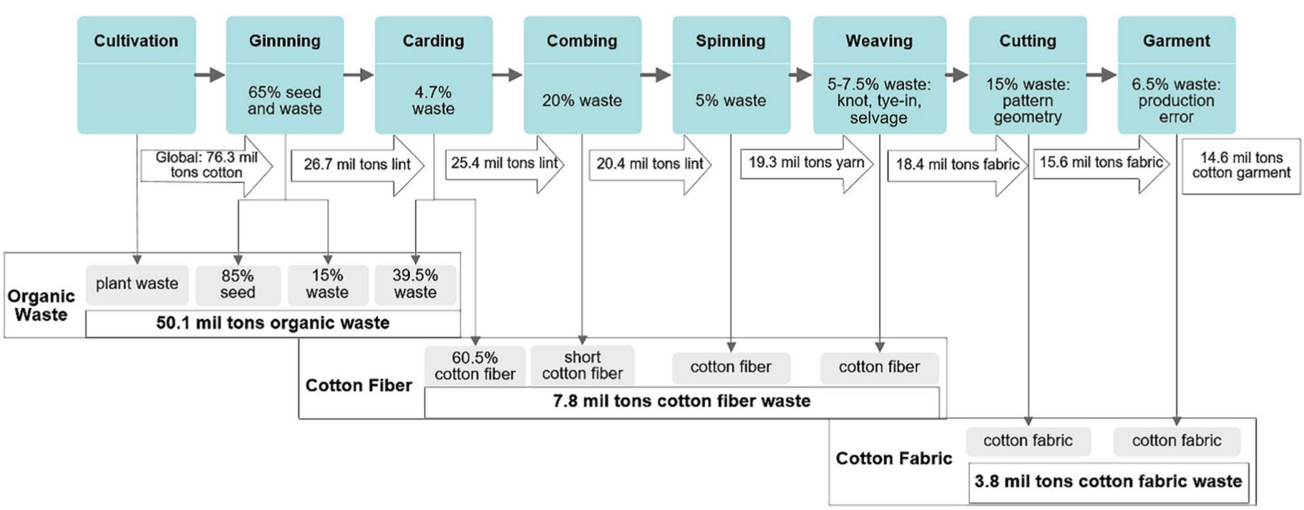


Fig. 4 Annual fiber waste generated during global cotton garment production from August 2018 to July 2019. Source: (Johnson et al. 2020)

20% of residue and, in the rowing and spinning, 5% more (Goyal 2021; Johnson et al. 2020).

In weaving, the amount of waste depends on the pattern design and model of the machine chosen. For example, on air-jet looms (air-jet drives weft yarns insertion), 5.0 to 7.5% of the cotton is removed as waste due to knotting, tying, selvedge, and human mistakes (Goyal 2021; Johnson et al. 2020).

Initiatives for the application of residues from the cotton chain are being increasingly researched and several solutions are proposed. The seed is used in oil production and for new planting but could also be applied to ethanol production, fertilizer, and oil spill cleaning (Johnson et al. 2020). For fibers and fabrics, it is applied in composting; recycling in new cotton yarn/fabric and blends, which implies a reduction in the absorption capacity; use of raw material in the transformation into regenerated fibers and paper making (Aishwariya 2018); composites; and thermal energy, in which cotton briquettes reached 16.80 MJ/kg and a cost of 0.006 V/kWh when used as fuel (Nunes et al. 2018).

Textile Waste in the Brazilian Chain

The generation of solid waste from the textile industry is enormous, with the most impacting stages of weaving and cutting fabrics for clothing, which generate a significant amount of hard fibers (from the spinning process), beaming, and soft fibers (from the yarns in the weaving process), and off-cuts (Haque and Majumder 2016). During the cutting process in conventional garment production, from 100% of the fabric generated, approximately 15 to 20% is textile waste. It is possible that, with a large number of apparel industries and the increase in consumption, this percentage could be much higher. Unfortunately, manufacturers do not consider these problems, because they often are worried about the total cost of product and profit, and ignore the cost of fabric (Rissanen 2013).

In general, the volume discarded of textile solid waste is around 10% of the total volume of used raw material. Thus, when comparing fabric consumption in Brazilian apparel manufacture, IEMI (2015) reported 1,199,893 tons (2014), which is estimated the generation of 120 thousand tons of textile waste or daily disposal of 330 tons by 29,942 clothing companies formally registered (IEMI 2015).

Interview at Cedro Têxtil

Cedro Têxtil is one of the main large size textile companies in Brazil with verticalized production (with spinning, weaving, and finishing) and 3400 direct employees. It has a monthly production of about 6.8 million linear meters or 168 million square meters of fabric per year. The main products are fabrics from cotton: denim, twills, and canvas, which compose the mix in fashion, professional lines and technical fabrics. The headquarters are located in the Belo Horizonte city (Minas Gerais – MG – state); the factories in Sete Lagoas-MG, Caetanópolis-MG, and Pirapora-MG cities; and the distribution center, in Contagem-MG, attending Brazil and abroad (Cedro Têxtil 2022).

The interview was conducted via e-mail with the company's cotton supplies manager, focusing on the identification of the main solid wastes and their destinations (Table 1). The decisions regarding waste management imply a variety of solutions. The classification of the waste type is following the NBR 10.004:2004 standard, with emphasis on class II — non-hazardous waste (II-A — non-inert and II-B: biodegradability, combustibility, and water solubility) (ABNT 2004).

Textile residues generated from the weaving process are as follows: raw tow and paint, iron, wood, selvedge (class IIA), destined for recycling; briquette/dirt (class II), animal feed, Zinabre (batteries), chemical products, packaging (class IA), co-processing, and incineration and organic waste, boiler ashes (class IIA) are sent to the municipal landfill.

Composites Obtained from PVC and Cotton Weaving Waste

PVC compound used in this research is flexible and transparent. Thus, composites produced with different shapes of cotton waste types can produce visual effects, though translucency, which needs to achieve the standard of the required mechanical properties. Different visual effects were obtained, which depend on the fiber size, colors, and dispersion form in the samples. Their esthetic attraction suggests

Table 1 Main waste types from Cedro Textile company according to hazard classification (NBR 10.004:2004) and destination

Waste types	Classification	Destination
Raw tow and paint, iron, wood, selvedge	IIA	Recycling
Briquette/fiber spots	II	Animal food
Zinaber (batteries), chemicals, packaging	IA	Coprocessing and incineration
Organic waste, boiler ashes	IIA	Municipal landfill

Source: Authors

the possibility of their employment in fashion products with sustainable appeal as a viable alternative (Fig. 5).

Higher percentages of residue were not feasible, and due to the low density of the fiber, its volume made the mixing process difficult. On previously research carried out with the same PVC formulation and process (two-roll mill) to prepare polymer and fibers blend, higher amounts of 10/20% of fibers as filler lead to a significant decrease of its mechanical properties, because of difficulty to process and mix the fibers due to high volume when compared to the neat PVC material. With the cotton waste, working with 10% of filler was difficult to obtain a homogenous mixture and a stable material. Even considering the filler from another natural source, bamboo sawdust, in formulations with 5.0%, 10%, and 20%, with and without NaOH treatment, the compared results showed lower amounts of filler were more promising, presenting slightly better mechanical results and no significant difference in treatment use (Cordeiro et al. 2021).

In the present study, material processed in two-roll mills showed a good dispersion of residues in the PVC polymer, which is demonstrated in Fig. 5. In the machine, the dispersion phase must be reached before plasticization, when samples become bright and ready to be taken out.

The results of composite's mechanical properties showed in most of them a decrease in tensile strength and elongation values, and an increase in Young's modulus values compared with pure PVC matrix (Fig. 6a–c, respectively). This trend was still reported in the literature, an analogous system of PVC and banana tree fiber as filler, in which pure PVC presented greater values for tensile strength than composites with fibers and the inverse for Young's modulus (Becker et al. 2014). In the same sense, another paper reported date palm fiber as PVC reinforcement also showed low interaction in the matrix, which tensile strength property decreased by 35–38% in the composites, when compared to pure PVC (13 MPa), even with fiber treatments, in mercerization (~8.3 MPa) and acetylation (~8.2 MPa), the gain in properties was subtle, which did not justify their use, compared to untreated fibers (~8 MPa) (Boussehel et al. 2019).

Decay behavior of mechanical properties of composites with fibers concerning pure matrix may be related to lack of adhesion between fibers and matrix. In this study, composites reinforced by fibrous in the proportion of 2.5% (w/w) presented the best results in tensile strength and elongation compared to other compositions (Fig. 6a and b). It is important to highlight that briquette residue (2.5%) had better dispersion in the matrix and presented the tensile strength in a slightly higher value when compared to the other residues. However, more studies must be done to better demonstrate this finding.

Shore A hardness values (Fig. 6d) show the presence of fibers regardless of the amount did not significantly change their values, which could indicate fibers do not influence hardness. For industrial applications, Shore A hardness is considered flexible when the values are less than 90 (Calafel et al. 2020) and which is in agreement with what was found in the experiment. In this way, as this type of polymer is flexible, one of the possible applications is shoe soles, in which the hardness property acts directly on comfort, by reduction of floor impacts and keeping firm the foot placement (Sun et al. 2017).

Morphologies of fracture surfaces of the PVC and PVC/cotton residues composites were examined at SEM micrographs (Figs. 7 and 8). From the examination of PVC/cotton residues composites specimens, morphological characteristics of each group of filler content were almost similar. It can be observed (Fig. 6a and b) cotton fibers and yarns are discontinuous and randomly oriented when incorporated into the PVC matrix.

Without any mechanical or chemical treatment, composites presented separation between PVC and the cotton fibers

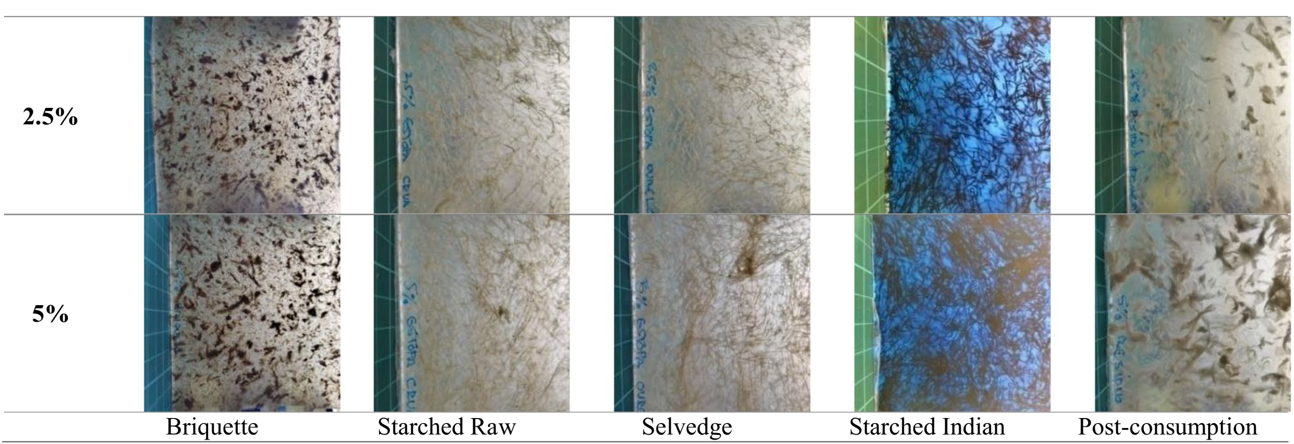


Fig. 5 Visual aspect of cotton/PVC composite boards employing 2.5% and 5.0% of reinforcement. From left to right: briquette, selvedge, starched, starched Indian, and domestic waste. Source: Authors

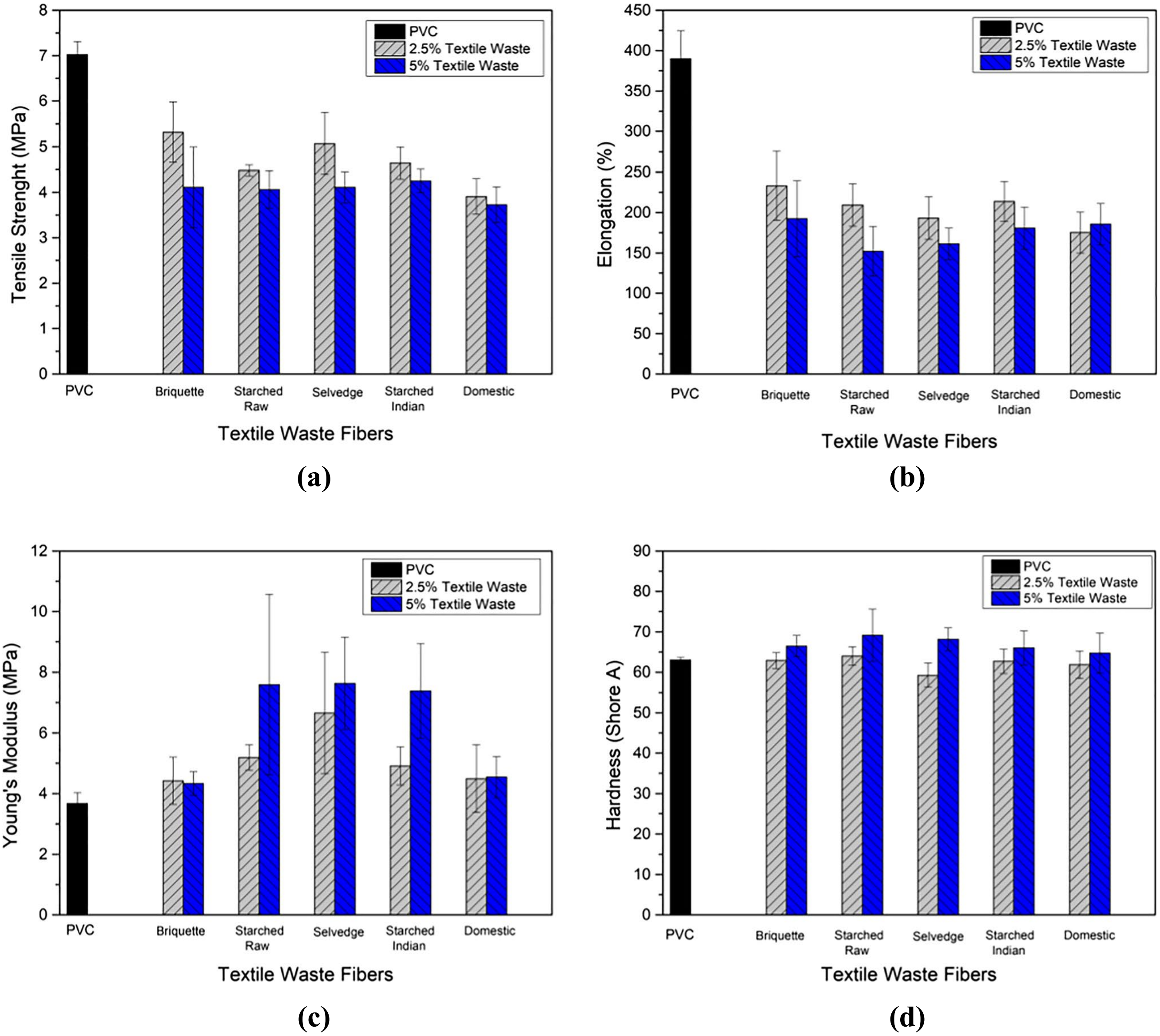
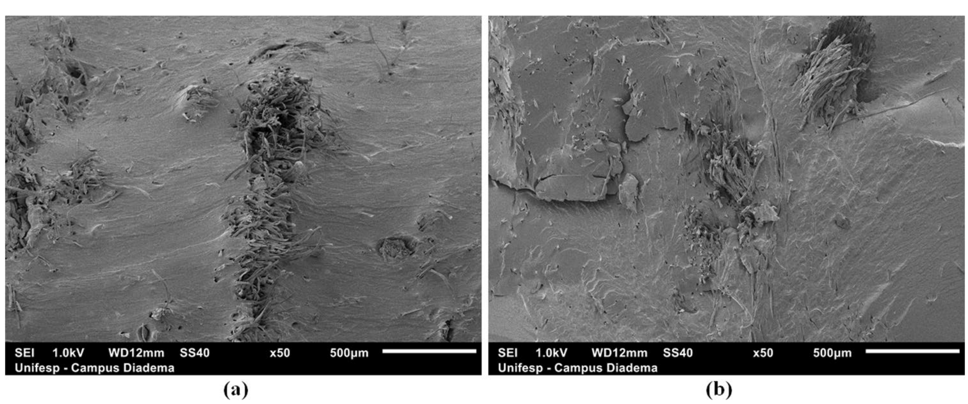


Fig. 6 Mechanical properties of pure PVC and composites reinforced with textile waste fibers. **a** Tensile Strength (MPa), **b** elongation (%), **c** Young's modulus (MPa), and **d** hardness (shore A). Source: Authors

Fig. 7 Morphological SEM image of composites reinforced with 2.5% of textile waste at × 50. **a** PVC/Briquette and **b** PVC/starched raw. Source: Authors



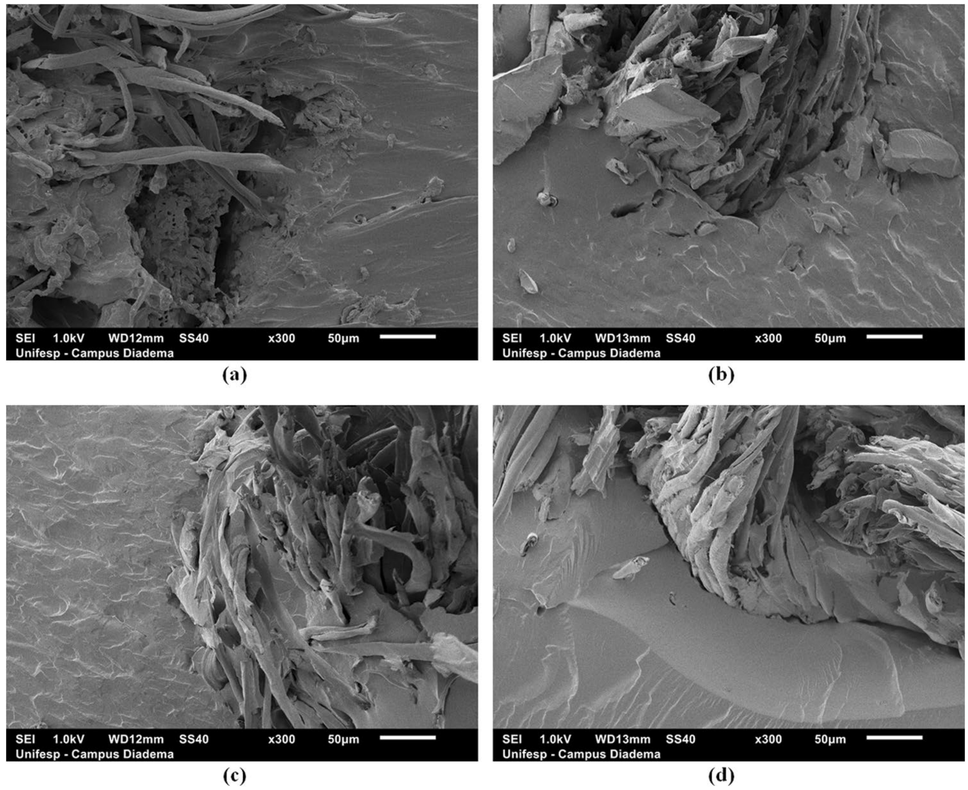


Fig. 8 Morphological SEM images of composites reinforced with 2.5% of textile waste at × 300. **a** PVC/Briquette, **b** PVC/starched Indian, **c** PVC/selvedge, and **d** PVC/domestic. Source: Authors

occurred, which is demonstrated at images (Fig. 8), because of incompatibility between hydrophobic polymer matrix and hydrophilic nature of cellulosic fibers (Syduzzaman et al. 2020; Mahdi et al. 2020). The micrographs show lower interface bonding at the gap between cotton and the PVC matrix. The lack of adhesion between fibers and matrix can also be observed by the decrease of the mechanical properties when compared with pure PVC matrix.

Conclusions

In this study, the variety of industrial residues can be verified, with emphasis on cotton textile residues from different stages of weaving. As destination for these residues, there are different application possibilities: fiber recycling for yarn production, thermal energy production, paper, composting, and composites.

The composites produced from PVC matrix and different types of cotton weaving waste (briquette waste, selvedge waste, starched waste, starched Indian, and domestic waste), in the proportions 2.5 and 5% (w/w), showed substantial differences in tensile properties. Composites with 2.5% fiber reinforcement showed greater chances of applicability, especially the composite with briquette reinforcement.

SEM analysis presented poor adhesion between fibers and the matrix. To improve mechanical behavior, treatments on the cotton residue could be applied to remove materials that cover the surface of the fibers (starch, lignin) and increase their roughness. For example, alkaline treatments and other physical and chemical treatments could be used to increase the adhesion between the cotton waste fibers and the polymer matrix.

Due to the transparent PVC matrix, incorporating low amounts of fibers can drastically alter and presents an unique visual aspect of the final material. With a sustainable appeal, cotton waste could be a viable alternative for applications and use with fashion accessories and products such as jewelry, buttons (without high mechanical requirements), shoes, and components (according to the applications and standards).

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Author Contribution AOTC, MCL, and LK carried out the experiments, data analysis, and led the drafting of the paper. JBR, RF, RCE, and CRM supervised the experimental work and data analysis. All authors contributed to the final manuscript drafting.

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Data Availability The datasets used and analyzed during this study are available from the corresponding author on reasonable request.

Declarations

Competing of Interests The authors declare no competing interests.

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