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Possibility of Recycling Textile Residues Into Paper-Based Products

Marina Vukoje*[1], Željka Bartolić[1], Katarina Itrić Ivanda[1], Rahela Kulčar[1], Sonja Jamnicki Hanzer[1]

[1] *University of Zagreb Faculty of Graphic Arts, Getaldićeva 2, 10000 Zagreb, Croatia.*

**Corresponding Author email: marina.vukoje@grf.unizg.hr*

Abstract

Despite the growing social trend of sustainability in the textile and modern industry worldwide, there is an urgent need to reduce the amount of waste generated by the global fashion industry. Numerous initiatives are being taken in Europe to address the sustainability of the fashion industry. And the textile industry is defined as a priority sector in which the EU can open the way for a carbon-neutral, circular economy. These key challenges could be addressed by making cellulose fibers from materials derived from textile waste. These fibers are biodegradable and therefore they are considered more environmentally sustainable than synthetic fibers. Also, textiles and clothing made from these fibers can be used as raw materials in recycling processes at the end of their life cycle, thus contributing to the development of the circular economy. New approaches to textile waste recycling are constantly evolving. Textile waste in the form of cotton fabrics proves to be a sustainable source of cellulose for paper production or as a material for the adsorption of toxic compounds. The aim of this paper is to explore the possibility of using textile waste as a raw material in the paper and packaging industry in order to support the circular economy.

Key words

circular economy, cellulose fibers, recycling, textile waste

1. INTRODUCTION

Wood is the main source of raw material used for the production of paper while non-wood fibres and recycled fibres (made from post-consumer waste paper) are increasingly finding their application in commercial paper production. The increased demand for paper and paper-based packaging, as well as increased deforestation, has encouraged the paper industry to seek new sources of raw materials for fiber isolation. It resulted in the numerus research of fiber isolation from new materials such as agricultural residues (bagasse, rice, straw, cotton stalks). These raw materials can be of major importance for the paper industry, in the areas where the wood is not available or due to other environmental concerns. Other non-wood fibres such as jute, hemp, flax, and cotton are natural materials widely used in textile industry. Cotton fibres are extensively used raw material in the textile industry, and their use in pulp and paper is very limited and mainly oriented to the production of specialty paper (currency paper) [1].

The textile and fashion industry are one of the leading environmental polluters due to the growing need and demand for textile products and economic development [2]. According to the Roadmap of the EU strategy for sustainable textiles by the European Commission, the Europeans consume an average of 26 kg of textiles per person per year and each item is used for a short time, resulting in the rejection of 11 kg of textiles per person per year, known as a “fast-fashion” phenomenon)[3]. This makes the textile industry a priority sector in which the EU can pave the way toward a carbon-neutral, circular economy, and announced an EU Strategy on textiles [3]. The textile industry is a significant polluter of the environment (high raw materials consumption and high levels of greenhouse gases emission) and therefore it should strive for sustainable development by using natural materials that can later be reused, recycled, or used as raw material for the production of some new products [4]. The textile waste recycling process can be categorized as chemical and mechanical recycling methods [5]. The new approach in many different industries is being transferred from the old linear economy to a circular model, where waste streams can be used to their maximum potential [5]. Different studies have shown the possibility of using different textile waste for the different purposes, for example, the production of new raw materials such as cellulosic ethanol [5], paper [6], as a material for the adsorption of toxic compounds [7]–[9] or as a material for a reinforcement of the composites materials for different applications [10], [11]. Primary recycling technologies, in which fibers are converted to new fibers, are preferable [12]. Pre-consumer and post-consumer textile waste can be produced from natural materials (silk, cotton, linen, hemp), synthetic materials (polyester and nylon), and regenerated materials (produced from natural polymers through processing - rayon, viscose) [5].

Textile waste made from natural fibers, is a promising source of cellulose [13]–[15]. Cellulose fibers recovered from waste textiles are the promising raw material for the production of paper and paper-based packaging. This fact is confirmed by the technological innovations and patent developments in this area [16]. According to Sanchis-Sebastiá et. al (2021) cellulosic fibers cannot be indefinitely converted to new fibers due to a reduced degree of polymerization in the pulping and regeneration process, which in the end degrades the mechanical properties of the fibers [12]. In addition, the authors claim that not all used garments are suitable for such a recycling process due to the lower quality of the fibers as a result of their use [12].

Using this waste as a raw material instead of the most common disposal technique - incineration, significantly reduces the impact on the environment. Textile waste used as a raw material resource, encourages the development of a circular economy in several industrial sectors (textiles, forestry, paper industry) while improving the sustainability of these industries. However, there is a certain awareness among people about the impact of these products on the environment, as well as what can be changed to reduce pollution. The development of the circular economy in the textile industry would contribute to the solution of disposal and usefulness of textile residues generated during the production of clothes. The isolation of cellulose fibers for example from textile wastes made from natural fibers which are biodegradable and therefore more environmentally friendly, can be a promising solution for problems caused by textiles waste generation in the environment. In order to improve this, the environmental policies worldwide should encourage the separate collection and proper sorting of all waste streams. European Commission in their Roadmap of the EU strategy for sustainable textiles emphasized the role of extended producer responsibility in promoting sustainable textiles and treatment of textile waste in accordance with the waste hierarchy and the implementation of the legal obligation to introduce a separate collection of textile waste by 2025 in European member states [3].

2. EXPERIMENTAL PART

2.1. Materials

For the purposes of this study, textile residues from small-scale clothing production were used. Natural materials such as denim, felpa, viscose, and render that contain a certain percentage of elastin were used. The used viscose material consists of 97% cotton and elastane, and commonly it is used for the production of T-shirts (Figure 1a). The material of denim consists of 100% cellulose fibers, denim was additionally treated with fabric bleach and therefore it is white (Figure 1b). There are different types of felpa material used to sew tracksuits. In this work, a 100% organic red cotton pile was used (Figure 1c). The fourth pink material is cotton render, which consists of 95% cotton and 5% elastane (Figure 1d). Elastane is a synthetic stretchy fiber, which is mostly used in textiles, as an additive to make them more elastic [17]. To make paper from textile material, first, it is necessary to manually chop the textile residue into smaller pieces with scissors (Figure 1a-d).

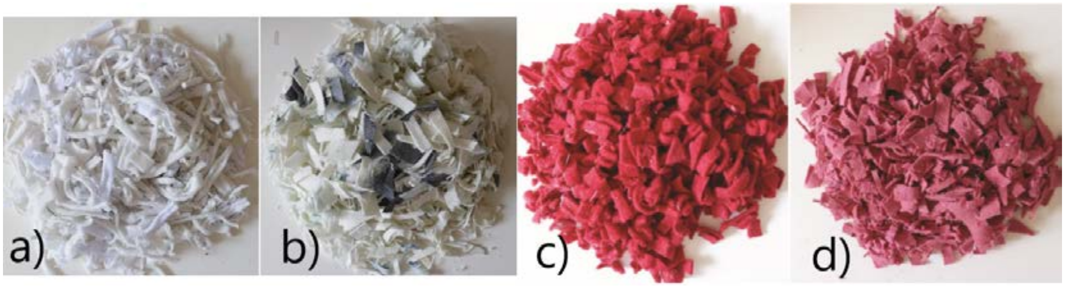

Figure 1. Chopped pieces of used textile materials: viscose (a), denim (b), felpa (c) and render (d)

For the preparation of paper samples, two types of materials were used: pure viscose waste residues (Figure 2a) and the mixture of all four materials (viscose, denim, felpa, and render) mixed in equal proportions (Figure 2b).

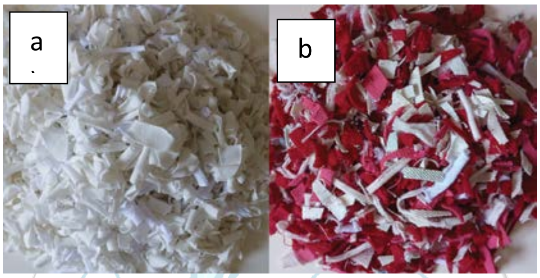

Figure 2. Chopped pieces of textile materials used for further preparation of paper from: viscose (a), and mixed materials (viscose, denim, felpa, and render) (b)

2.2. Methods

After shredding the textile materials, the materials were prepared for alkali cooking. The process was conducted by placing the waste textiles in 1 wt.% sodium hydroxide ($NaOH$) solution at a ratio of 1:2. The mixture was then heated to boiling and cooked for 2 h. After pulping, the pulped fibers were washed with deionized water until a neutral pH was achieved. Due to the lack of professional equipment and devices for mechanical processing of textile residues, an alternative approach for textile processing was used, i.e. a blender was used to separate and grind textile fibers. During mechanical processing using a mixer, the textile fibers are separated. In addition, a disintegrator was used after the blender, which in this case was used for mixing of produced textile pulp. The resulting pulp was stirred using a disintegrator (Enrico Toniolo) for 10 minutes in 2L of water to further separate the fibers within the pulp.

Paper samples were made on a laboratory manual machine for the preparation of laboratory paper sheets (A4 format), i.e. papers made of viscous material and papers made of a mixture of four materials: viscose, denim, felpa and render (Figure 3).

Figure 3. Preparation of laboratory paper sheets

Laboratory sheets of mixed textile and viscose paper, made on a manual paper sheet-making machine (Figure 3), were used to determine the tensile properties and tear resistance of the produced paper. In addition, FTIR spectroscopy was used for the evaluation of the chemical composition of prepared samples as it is the most acknowledged analytical technique in the analysis of textile fibers [17].

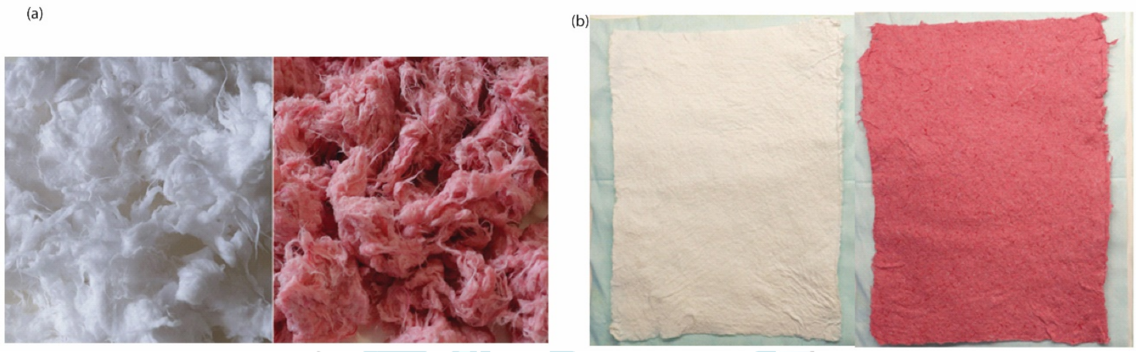

Figure 4. Visual presentation of textile fibers after the alkaline process and blending (a), and laboratory paper handsheets made from textile residues (b)

2.2.1. Determination of mechanical properties

Prepared paper samples for mechanical characterization were conditioned according to ISO 187 standard. The basic weight of produced papers was determined according to ISO 536.

Determination of Tensile breaking properties was performed using the Frank testing device. Testing was carried out according to ISO 1924-1 standard. The papers are cut into strips 15 mm wide and up to 250 mm long. The results were obtained from the average of 10 tested samples.

Tensile Strength (σ_T^b) is the tensile force required to produce a break in a strip of paper or paperboard, expressed in kN/m. It is determined according to equation 1, as the ratio of the mean breaking force $\overline{F_t}$ (N) and the width of the sample b (mm), and is expressed in kN/m:

$$\sigma_T^b = \frac{\overline{F_t}}{b} \tag{1}$$

Tensile index σ_T^w (Nm/g) is the ratio of tensile strength σ_T^b (kN/m) and paper's basis weight m_a, expressed in grams per square meter (g/m^2). In this way, the tensile index allows the comparison of the results measured on paper samples of different weights.

$$\sigma_T^w = \frac{\sigma_T^b}{m_a} \tag{2}$$

Tearing resistance is the force required to tear the paper from an initial cut. The tear resistance of paper was carried out in accordance with the standard HRN ISO 1974 Paper - Determination of tear resistance

(Elmendorf method) using the Elmendorf Tearing Tester (Frank PTI). The results were obtained from the average of 10 tested samples. The test was performed on samples measuring 65 x 80 mm (2 pieces) which were cut using a template. The scale is calibrated so that as a result it gives the mean force in millinewtons (mN), which needs to be applied to tear 16 sheets simultaneously. To measure the tearing resistance of papers that have higher strength properties, the measurement can be performed on a smaller number of samples, but then the measured value should be recalculated according to Equation 3.

$$F = \frac{16}{n} \cdot F_n \qquad (3)$$

Where:

F is the tearing resistance, expressed in mN;

F_n is the mean scale reading, expressed in mN, which refers to the number (n) of sheets thorn simultaneously;

n is the number of sheets torn simultaneously.

The results of the test are further expressed as the tear index (X) which is the tearing resistance (mN) of the paper divided by its basis weight (g/m^2). The result is expressed in millinewton square meters per gram (mN·m^2/g) and can be calculated according to Equation 4.

$$X = \frac{F}{m_a} \qquad (4)$$

2.2.2. Fourier Transform Infrared Spectroscopy (FTIR Spectroscopy)

The ATR spectra of the paper samples produced from textile residues were measured using the Shimadzu FTIR IRAffinity-21 spectrometer (Shimadzu), with the Specac Silver Gate Evolution as a single reflection ATR sampling accessory with a ZnSe flat crystal plate (index of refraction 2.4). The IR spectra were recorded in the spectral range between 4000 and 600 cm^{-1} at 4 cm^{-1} resolution and averaged over 15 scans.

3. RESULTS AND DISCUSSION

Due to the absence of professional equipment required for the isolation of cellulose fibers from the textile wastes, this was the most difficult part of the process. Despite that, cellulose fibers have been successfully isolated from the used textile wastes which was confirmed by the FTIR spectroscopy (Figure 5).

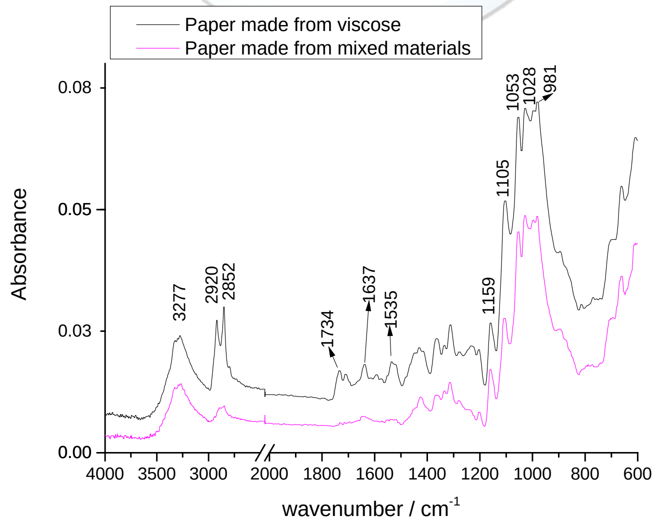

Figure 5. FTIR spectra of laboratory paper handsheets made from textile residues

Changes in the chemical structure of papers made from textile residues were examined by ATR-FTIR. Figure 5 shows the spectra of papers made from viscose and mixed materials, respectively. The obtained spectra correspond to the cellulose structure, but another vibrational band can be seen as well. The cellulose characteristic bands are present in both samples. The O–H stretching vibrational band (3600–3100 cm^{-1}) and the bands between 900 and 1200 cm^{-1}, covering glucose ring stretching (981 cm^{-1}), CO stretching (1053 and 1028 cm-1), glucose ring asymmetric stretching (1105 cm^{-1}), and C-O-C asymmetric stretching (1159 cm^{-1}). Moreover, the FTIR spectra of studied samples differ significantly in the spectral range 1800 – 1200 cm^{-1}, and in the spectral range 3000 – 2000 cm^{-1}. This points to the presence of elastin in viscose-containing paper [17]. Elastane, namely synthetic fibers containing at least 85 wt% of high molecular weight segmented poly-urethane resin, is mostly added in textiles to make materials more elastic [17],[18]. The vibrational band at 1734 cm^{-1} is carbonyl stretching vibration. In the spectral range between 3600 and 2600 cm^{-1} is displaying broad hydrogen-bonded N–H stretching peaks from the urethane bond in the elastane fibers. This band overlaps with the –OH stretching from cellulose. The C–H stretching peaks from aliphatic and aromatic groups originate from the elastane fibers. This region shows a band related to the: amide I at (C=O) 1636 cm^{-1}, amide II (N–H) at 1535 cm^{-1} [18]. The FTIR spectra of paper made from mixed materials is similar to the spectrum of cellulose. In addition, the he C-H stretching vibration in the spectral range from 2920 – 2850 cm^{-1} is registered [17].

Tensile strength and tearing resistance of paper are one of the most important paper properties and indicate the behavior of paper in various end-use situations. These properties are an important factor in packaging performance as well. These properties are affected by the different parameters, such as the length of cellulose fibers and their orientation, the degree of compression of the sheet during production or finishing, the ratio of length to fiber diameter, fiber direction, character, and arrangement of connections between fibers and by various factors related to the production of sheets of paper (surface sizing, additives), drying stresses created in the dryer press section of the papermaking machine. Beating/refining of the pulp tends to improve tensile strength because it increases the interfiber bonding. The orientation of the fibers in the paper is related to the running direction of the web, which is customarily referred to as the machine direction (MD), and the lateral direction as the cross-machine direction (CD). Tensile strength of paper is the highest in the paper direction of the main fiber orientation while tearing resistance is greater in the CD because the tear goes across the fibres and is lower in the MD where the tear propagates along the fibres [19].

The results of the mechanical resistance of paper samples (made on a hand-made machine) show that the resistance of viscose paper samples is slightly higher than that made of mixed paper samples. This may be caused by the presence of elastane in the produced viscose paper, i.e. the elastane gives a stretchy property to paper during tear strength test. With the absence of elastane in the paper, the tensile strength is reduced (in the case of paper made from mixed materials). It is important to emphasize that in this study, for the obtained paper samples typical fiber orientation, which is seen in machine-produced papers, is absent. This can also affect the paper's mechanical properties. Moreover, the obtained paper are missing the additives which are usually added in the paper production. Thus, the results obtained are significantly lower than the results of mechanical properties of commercial papers, commonly available on the market. To improve paper mechanical properties, additional process optimization is required. Paper with mechanical properties such as those presented in the Table 1 wouldn't be good to use in the printing process where high speeds and rotations are present. The runnability of the paper in the printing press is crucial for the productivity of the printing process. Good runnability assumes that the paper passes through the printing press without any web breaks (reel paper) or stoppers (sheet paper). This requires sufficient strength of the paper (tensile strength, tear resistance) and bending stiffness.

Table 1. Mechanical properties of papers made from textile residues

Property	**Paper made from viscose**	**Paper made from mixed materials**
$\boldsymbol{\sigma_T^b}$ **(kN/m)**	0.077826	0.071286
$\boldsymbol{\sigma_T^w}$ **(Nm/g)**	0.298184	0.293358
***F*(mN)**	283.33	217.33
X **(mN·m²/g)**	1.085555	0.894362

4. CONCLUSIONS

This paper presents the possibility of using textile waste made from natural fibers for the isolation of cellulose fibers and its use in paper production. The results of the mechanical properties determination showed clear shortcomings of the textile fiber paper. The mechanical properties determination showed slight variations between the two studied samples. The results of tensile index of viscose paper and paper made from mixture of materials is almost the same, while slight differences are observed for the tear index, whit somewhat higher values for viscose containing paper. With this result, we can conclude that for both groups of paper it is necessary to improve the mechanical properties by further process optimization, but also to determine the flow direction of the fibers which in the end influence the mechanical properties of paper. In addition, the mechanical properties of paper can be influenced by the length of the fibers as well. The absence of technical equipment for the processing of textile waste was an additional limitation of this study, but despite that fact, this paper has shown that there is a possibility of recycling textile residues made from natural fibers to produce new raw materials. i.e., a paper which is otherwise obtained from other natural resources. This can be an example of the circular economy within the textile industry, where the association of larger or smaller textile and fashion industries is formed with the aim of disposal of textile residues generated during production. The designed system of textile waste recycling for the purpose of processing new raw materials encourages additional association with other industries. Also, this paper presents an adequate solution to reduce environmental pollution during small or big production within the textile and fashion industry. It is important to emphasize that a preliminary study was presented here, which included only one small segment of the textile industry. To develop the production of textile fiber paper in a higher percentage and a higher scale, the process itself requires further research and optimization. For this reason, the optimal concentration of alkali and duration of alkali treatment of textile fibers should be further analyzed. It is also necessary to find the optimal ratio of the textile fibers and alkali in the process, in order to obtain good quality fibers. The process itself also requires the selection of the ideal technology for chopping large textile pieces into smaller ones, which proved to be the most demanding step in this study.

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