REVIVING CELLULOSE-BASED INDUSTRIAL TEXTILE WASTES INTO RECYCLED PAPERS

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This study evaluates the feasibility of upcycling cellulose-based industrial textile wastes as reinforcement materials in recycled paper production. Waste cotton, flax, and hemp fibers were incorporated into recycled paper pulp at weight ratios of 25, 50, and 75 wt% to examine their effects on the physical and mechanical properties of handmade papers. Physical properties (basis weight, thickness, and water absorption) and mechanical performance (tensile index and tensile energy absorption index) were characterized. The results showed that textile fiber reinforcement significantly improved the mechanical performance of recycled papers. Cotton-reinforced papers exhibited increasing tensile strength and energy absorption with higher fiber content, whereas flax- and hemp-reinforced papers achieved maximum strength at lower fiber ratios. The highest tensile index (49.08 Nm/g) and tensile energy absorption index (3.11 J/g) were achieved with 75 wt% cotton fiber reinforcement. Water absorption behavior was strongly influenced by fiber type and crystallinity, showing an inverse relationship with mechanical performance. The findings demonstrated that cellulose-rich textile waste can serve as a sustainable reinforcement for recycled paper, supporting circular material use between the textile and paper industries and enabling applications in art, packaging, and value-added paper products.

Keywords: recycled papers, textile wastes, upcycling, recycling, cellulose

INTRODUCTION

The migration of humans from rural to urban regions has resulted in notable shifts in patterns of production and consumption, which are characterized as a break from nature. The industrial revolution brought new technologies that increased production volume, which in turn raised the demand for raw materials necessary for manufacturing. However, the resources are limited and insufficient to meet the rising demand. This circumstance necessitates the economical use of resources and motivates scientists to look for substitute raw materials.[1,2]

Due to its wide spectrum of continuously needed and consumed products, the textile industry, as one of the fastest-growing industries, impacts the environment severely. The textile industry's excessive energy consumption, microplastic release, wastewater discharge, and carbon dioxide emissions damage ecosystems in all aspects. By 2050, the textile sector is predicted to account for 26% of the world's carbon footprint based on current trends. In addition, 22 million tons of microplastics resulting from this industry are thought to have entered the ocean,[3] highlighting the urgent need for sustainable interventions, such as the use of environmentally friendly raw materials, the implementation of energy-saving production methods, efficient logistics management, and the adoption of circular economy strategies throughout the textile supply chain.[4] Moreover, the textile sector generates a significant quantity of solid waste, which poses a risk to the ecological balance. This is evident in both the industrial wastes created during the manufacturing process and the domestic textile wastes disposed of by consumers after their useful life span. It is critical to recycle these wastes and utilize them as raw materials in the same or different industries.[5]

Hemp stands out as one of the oldest fibers and is known as the most environmentally friendly option of all natural fibers.[6] Although the usage of this fiber in the textile industry is increasing day by day from a sustainability perspective, its high pectin and lignin content makes this fiber unspinnable and restricts its processability in the textile industry, resulting in low-quality products.[7] Thus, hemp fiber is widely preferred as a reinforcement material in composite structures due to its high strength and stiffness. In recent years, there has been an exponential increase in the use of hemp in many different application areas.[6] However, hemp production is restricted in many parts of the world because of its association with drug production, which has also limited its widespread use in both textile and other sectors.[8,9] Flax is known as the primary raw material for value-added products of several sectors, such as textile, composites, paper and industrial/nutritional oil. Throughout history, long flax fibers have become increasingly popular in the manufacture of high-quality clothing, while short fibers that become waste in the long fiber production line have been used for lower-value products.[10] The production of flax and hemp is intricate and demands a high level of expertise at every stage, which prevents the widespread adoption of these fibers in the textile industry.[11] Cotton fiber is the dominant natural fiber in the worldwide textile industry. However, the harmful impacts of this fiber on the environment and living organisms are becoming more well-known. Water stress is brought on by the massive volume of water required to irrigate cotton crops, and pesticide use during irrigation is hazardous for both the environment and human health.[3] On the other hand, textiles made of cotton fiber generate a significant quantity of solid waste both during the manufacturing process and once the product is delivered to the customer. Post-consumer textile waste, known to contain 54.7% cotton, 22.6% polyester, 6.2% acrylic, 5.7% viscose, 4.7% wool, 3.5% poliamide, and 2.7% of all other fibers by weight, underscores the crucial importance of recycling cotton waste.[12]

The paper industry is one of the top five industries in the world. Given its cultural and industrial applications and status as an indicator of civilization, paper is one of the most essential necessities of our day.[13] On the other hand, the manufacture of paper uses billions of cubic meters of water annually and generates a massive quantity of effluent that needs to be treated. Accounting for 42% of global industrial effluent, the paper sector is the third largest source of wastewater worldwide.[14] Contrary to common assumptions, today's paper usage is increasing, which forces paper manufacturers to look for alternative raw materials due to dwindling natural resources, the long growth period of forests, pollution, and rising energy prices. Cellulose is the primary material used to make paper. Trees, annual plants (including cotton, bamboo, and hemp), and recycled paper waste are suitable sources of cellulose.[15] The sustainability of cellulose pulp, which is also indispensable for different sectors (medicine, gastronomy, household goods, *etc*.), is crucial and it is known that the paper sector alone consumes more than 10% of the world's wood production.[16] The high quality of paper made from wood fibers is ensured by its length, low number of non-fibrous cells, and low ash content; nonetheless, overuse of wood results in ecosystem exploitation and upsets the ecological balance.[17] Compared to wood, non-wood resources provide excellent fibers for paper production due to their high quality and fast pulping properties. Globally, non-wood resources account for 5-7% of paper and pulp production.[18] Non-wood materials like bamboo, straw, and hemp grow faster than wood, ensuring a quicker, steady fiber supply. Agro-based paper production also uses up to 90% less water and 60% less energy than wood-based methods.[19] Plants used to make pulp, like elephant grass, giant reed, and reed canary grass, are categorized as short-fibers, whereas hemp, sisal, kenaf, jute, and flax are classified as long-fibers, mostly utilized in the textile industry.[20]

Many alternate non-wood sources of raw materials have attracted research interest for producing handmade paper. These include fibers from the food industry, such as banana fibers,[21-23] rice straws,[24] sugarcane bagasse,[23,25] and maize husk;[25] some local plants, such as *Pteroceltis tatarinowii*,[26] which is an endemic Chinese plant; Lokta bushes grown in the Nepali Himalayas;[27] and Brazilian exotic invasive weed species like *Arundo donax* L.[28] and the *Agave tequilana* plant native to North America;[29] as well as flowers like water hyacinth.[30]

In addition to these innovative raw material sources, it is possible to find a limited number of studies in which waste cellulose sources are evaluated as raw materials. Shredded currency waste of the Reserve Bank of India[31] and waste medical personal protective equipment kits[32] are among the noteworthy examples of waste sources. Also, jute wastes can be utilized to manufacture mostly brown-colored handmade papers.[33] In a study, Amode and Jeetah[34] explored Mauritian hemp as a sustainable alternative to wood for printing paper. Using soda pulping, they produced papers from 100% hemp and blends with elephant grass fibers and wastepaper. The 100% hemp paper showed properties closest to commercial paper, and adding starch further improved the printability and mechanical properties (tensile strength, burst strength, and abrasion resistance) of paper.[34] In another novel study conducted by Shiddique *et al.*,[35] cotton woven shirts that had become consumer waste were used in papermaking to produce bio-based packaging material using wet-laid and TPU coating processes. In the study, it was seen that papers could be produced successfully, but only the effects of TPU coating on the performance of the packaging were examined and raw material variables were not included.[35] On the other hand, although hosiery waste, tailor's cuttings, and, to some extent, waste paper are among the traditional raw materials used by the Indian handmade paper industry,[22,36] there are no studies on a global scale in which industrial textile waste is evaluated and studied scientifically.

This study aims to present a scientific perspective on the use of locally and traditionally used textile waste in handmade papers and to discuss their contributions to the performance of paper comparatively. In this context, this study focuses on producing recycled and 100% natural handmade paper from the cellulosic wastes of the paper and textile industries. The effect of cellulosic textile fiber reinforcement on the mechanical and physical properties of papers is examined by mixing varying amounts of waste cotton, hemp, and flax fibers into the pulp obtained from paper waste. The findings of this study will pave the way for sourcing the cellulosic raw material essential for paper production from extensive textile waste deposited in landfills monthly. Consequently, the research will play a role in diminishing solid waste stemming from both the textile and paper industries, lessening the environmental impact caused by these sectors, and acquiring performance attributes that enhance the value of the current handmade paper industry.

EXPERIMENTAL

Materials

Waste paper labels without additional surface coatings were supplied by Oztek Etiket and used as the recycled paper source. Waste plant-based textile fibers, including cotton, flax, and hemp, were utilized as supplementary cellulose-rich reinforcement materials (Fig. 1). Starch and potassium aluminum sulfate (alum) were used as wet-end additives during paper formation to improve inter-fiber bonding and paper integrity.[37,38] All additives were applied at fixed amounts for all samples to ensure consistent processing conditions. Textile fibers were subjected to a mild alkaline pretreatment prior to mechanical beating. Oak ash and chlorinated lime were employed as alkaline agents to adjust fiber acidity, promote fiber swelling, and facilitate subsequent fibrillation.[39] The alkaline treatment was applied uniformly to all fiber types and followed by thorough rinsing with distilled water until a neutral pH was achieved. Chlorinated lime was additionally used to provide limited brightening of the fibers; however, no intensive chemical bleaching was performed. Distilled water was used throughout all the stages of pulp preparation and papermaking to minimize the influence of dissolved ions and impurities on paper properties.

Figure 1: (a) Recycled cellulosic fibers (hemp, cotton, and flax), (b) waste paper

Methods

Size preparation

The sizing solution was prepared using distilled water, starch, and potassium aluminum sulfate (alum). Starch was dispersed in distilled water at a concentration of 83 g/L and heated under continuous stirring at 90 ± 2 °C for 30 minutes until a homogeneous and viscous solution was obtained. Potassium aluminum sulfate was then added to the sizing solution at a concentration of 3.3 g/L to improve paper integrity and resistance against biological degradation. The prepared sizing solution was allowed to cool to room temperature prior to its controlled addition to the pulp suspension. The same sizing formulation and addition protocol were applied to all paper samples to ensure consistent wet-end conditions and enable reliable comparative analysis.

Recycled paper-based pulp preparation

Waste paper labels without additional surface coatings were used as recycled paper source. The waste papers were first manually cut into approximately 2–3 cm² pieces and soaked in distilled water at room temperature for 24 h to allow complete fiber swelling using a waste paper–to–water ratio of 1:5 (w/v). Following soaking, the paper pieces were mechanically disintegrated using a laboratory-scale mixer (Proter, 700 rpm, 10 min) to obtain a coarse pulp suspension. The coarse pulp was subsequently diluted by adding distilled water to reach a fourfold dilution ratio and further refined using a high-speed laboratory blender (New Nova S40, 1300 rpm, 5 min) under controlled conditions until a homogeneous fine pulp suspension was obtained. A prepared sizing solution was added to the diluted pulp at a dosage of 500 mL per batch to promote inter-fiber bonding. For sample formation, the pulp suspension was transferred to a 50 L forming vat containing 25 L of distilled water and 500 mL of sizing solution. The pulp consistency in the vat was adjusted by adding fine pulp at a ratio of 1 L of pulp per 10 L of water, corresponding to 2.5 L of pulp for 25 L of water, resulting in a consistent fiber concentration across all samples. To ensure reproducibility, identical mechanical treatment times and rotational speeds were applied during pulp preparation for all batches. The prepared pulp was stored in aqueous suspension and used within 24 h to minimize fiber degradation and changes in suspension properties.

Recycled fiber-based pulp preparation

Waste cotton, flax, and hemp fibers were manually cut into lengths of approximately 5–10 mm to facilitate uniform processing before pulping. The fibers were then subjected to a mild alkaline pretreatment to reduce acidity, promote fiber swelling, and improve fibrillation prior to mechanical beating. The alkaline treatment was carried out using a mixture of chlorinated lime and oak ash dispersed in distilled water. This treatment was applied uniformly to all textile fiber types to ensure comparable chemical exposure. Following alkaline treatment, the fibers were thoroughly rinsed with distilled water until a neutral pH was achieved.

After chemical pretreatment, the fibers were mechanically beaten using a laboratory-scale mechanical beating process (Hollander beater) to reduce fiber length and enhance fibrillation. Identical mechanical beating conditions for 2-3 hours were maintained for all fiber types to ensure comparability among samples.

The prepared textile fiber pulps were blended with recycled paper pulp at weight ratios of 25, 50, and 75 wt% based on oven-dry fiber content. All blends are mixed under identical conditions to ensure homogeneous fiber distribution before paper formation. The pulp consistency and total fiber content were kept constant for all samples to eliminate variations arising from suspension concentration.

Paper production

Handmade papers were produced using a laboratory-scale wet-laid papermaking process (Fig. 2). Firstly, the pulp suspension was gently stirred to achieve homogeneous fiber dispersion. Papers were formed by immersing a forming screen into the pulp suspension and allowing fibers to deposit uniformly onto the screen surface. The screen was moved in a controlled manner within the vat to promote even fiber distribution and minimize flocculation. After paper formation, excess water was removed by gravitational drainage followed by mechanical dewatering. The wet papers were transferred onto felt fabrics and subjected to uniform manual pressing to further reduce water content. The formed papers were air-dried under ambient laboratory conditions and subsequently dried to constant mass. All paper samples were conditioned at 23 ± 1 °C and 50 ± 2% relative humidity for at least 24 h in accordance with standard paper testing practices. After air drying, the papers were subjected to pressing at a pressure of 1000 bar for 24 hours to improve surface smoothness and paper consolidation.

To maintain consistent paper mass, a fixed amount of pulp corresponding to approximately 250 g (wet mass) per A4-sized sheet was withdrawn from the vat for each paper produced. After each paper formation, the pulp concentration in the vat was restored by adding a proportional amount of prepared pulp, ensuring constant suspension conditions throughout the production process.

Table 1 provides the sample codes of the produced handmade papers, along with the weight ratios (WR) of the recycled textile fibers. In the coding, letter R was used for recycled paper, C for cotton, F for flax, and H for hemp. The following numbers indicate the weight percentage of the relevant fiber in its content. The manufactured handmade papers from different raw materials can be seen in Figure 3.

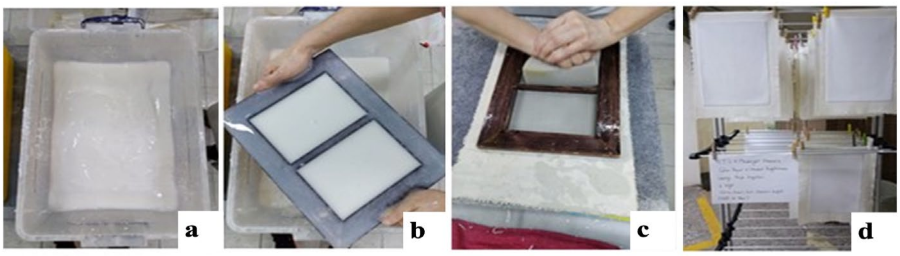

Figure 2: Paper production steps: (a) forming vat, (b) screen filled with pulp, (c) draining off excess water and (d) hanging papers to dry

Table 1
Paper codes and textile fiber contents

Paper type	Paper code	Cotton fiber WR (%)	Flax fiber WR (%)	Hemp fiber WR (%)
Recycled paper	R	-	-	-
Recycled paper+ Cotton fibers	RC_25	25	-	-
	RC_50	50	-	-
	RC_75	75	-	-
Recycled paper + Flax fibers	RF_25	-	25	-
	RF_50	-	50	-
	RF_75	-	75	-
Recycled paper + Hemp fibers	RH_25	-	-	25
	RH_50	-	-	50
	RH_75	-	-	75

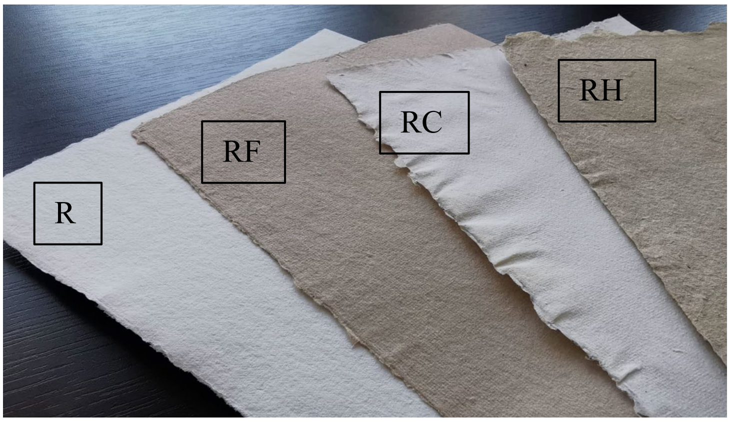

Figure 3: Handmade paper samples including recycled paper pulp (R) and different waste fibers (RF, RC, and RH)

Performance analyses
Physical tests

Sample weights were quantified employing a precision scale, and basis weight values were subsequently computed. The thicknesses of the samples were assessed utilizing a Standard Gage (Hexagon Metrology). The outcomes are presented as mean values along with their corresponding standard deviations (SD).

Water absorption capacity test

The TAPPI T 441 test method was followed while conducting the water absorption test. After being dried for five minutes at 105 °C in an oven to eliminate moisture, samples were cooled and weighed under ambient conditions. Following the measurement of the dry weight, the samples underwent submersion in water for 45 seconds. After that, the samples were removed from the water and placed between drying sheets. A roller was used to apply light pressure to the samples to remove any remaining water, and then each sample's wet weights were measured. The water absorption ratio was subsequently computed using both wet and dry weights. Each sample group underwent this process for a minimum of five samples, and the average results were calculated and given with SD values.

Tensile tests

Tensile properties of the paper samples were determined using a Zwick–Roell Z005 Universal Testing Machine in accordance with BS EN ISO 1924-2:2008. All samples were conditioned at 23 ± 1 °C and 50 ± 2% relative humidity for at least 24 h before testing. Rectangular test specimens with a width of 15 mm and a gauge length of 21 mm were cut from each paper sample in both the machine (0°) and cross directions (90°). A minimum of five specimens were tested for each sample group and direction. Tensile tests were performed at a constant crosshead speed of 20 mm/min. The tensile strength was calculated as the maximum tensile force divided by the initial specimen width and reported in kN/m. In addition, tensile energy absorption (TEA), defined as the area under the force–elongation curve, was calculated for each specimen and reported in J/m².

Since the produced paper samples exhibited variations in basis weight depending on fiber type and reinforcement ratio, tensile properties were additionally normalized to eliminate the influence of paper mass on mechanical performance. Accordingly, the tensile index (Nm/g) and the TEA index (J/g) were calculated by normalizing the tensile strength and tensile energy absorption values with respect to the corresponding basis weight of each sample. This normalization approach enables reliable comparison of intrinsic mechanical performance among paper samples with differing basis weights and is commonly employed in paper characterization studies.[40] The normalized tensile parameters were used alongside absolute values to support the discussion of fiber type and reinforcement effects. All results were given as mean and SD values.

RESULTS AND DISCUSSION

Physical tests

Table 2 shows that the paper produced entirely from recycled paper (R) has a higher basis weight than that of blend papers (RC, RF, and RH). This can be explained by the shorter fiber composition in papers made solely of recycled paper, which has improved the starch's binding function[41] and reduced the air gaps, resulting in an increase in basis weight. Examining the blend papers reveals further evidence in favor of this. It has been noted that regardless of the type of raw material, the basis weight values of the produced papers decrease as the amount of comparatively longer textile fibers increases. A reduction in sample thickness has also been observed in the same circumstances.

When the blend papers are examined among themselves, the papers with the highest textile fiber weight ratio (75%) are compared in order to make the most accurate interpretation. In this case, it is seen that RC_75 has the highest basis weight (161.20 g/m^2), followed by RF_75 (144.96 g/m^2) and RH_75 (141.47 g/m^2), respectively. This observation can be elucidated by the variation in fiber density ranges within the samples, including cotton fibers (1.51-1.60 g/cm^3), flax fibers (1.30-1.50 g/cm^3), and hemp fibers (1.07 g/cm^3).[42]

Table 2
Average basis weight and thickness values

Paper code	Basis weight ± SD (g/m^2)	Thickness ± SD (mm)
R	344.50 ± 1.33	0.69 ± 0.06
RC_25	209.42 ± 1.06	0.36 ± 0.03
RC_50	202.86 ± 0.71	0.35 ± 0.01
RC_75	161.20 ± 0.45	0.24 ± 0.01
RF_25	264.26 ± 1.09	0.43 ± 0.06
RF_50	186.56 ± 0.32	0.39 ± 0.02
RF_75	144.96 ± 0.67	0.39 ± 0.02
RH_25	205.77 ± 0.89	0.43 ± 0.02
RH_50	188.50 ± 0.75	0.36 ± 0.08
RH_75	141.47 ± 0.64	0.34 ± 0.01

Water absorption capacity test results

The water absorption capacity results presented in Table 3 reveal that when the textile fiber ratio increases, the cotton blend papers' water absorption values decrease, but the flax and hemp blend papers exhibit the reverse trend. The crystallinity and cellulose content of the fibers both contribute to this explanation. While the cellulose ratio in cotton is over 90%, it is approximately 80% in hemp, 75% in flax, and 40–50% in wood.[43,44] Moreover, the cellulose in cotton has the highest molecular weight and highest structural order, that is, high crystallinity and fibrillar orientation, compared to other plant fibers.[45] During water absorption, water molecules fill the gaps between the cellulose fibrils and microfibrils in the fiber.[46] Thus, tightly packed and oriented cellulose fibrils negatively affect the water absorbency. This supports the fact that the highest water absorption rate is obtained at RC_25 (133.24%), and as the cotton content increases from 50% to 75% by weight, the water absorption rate decreases to 116.50% and 105.94%, respectively.

Upon analyzing the test results for the RF samples, it is evident that the flax blend sample group's water absorption percentages are higher than those of the cotton blend samples. The observed phenomenon can potentially be attributed to the comparatively lower cellulose content (75%)[45] and diminished crystalline ratio (57%)[43] of flax fibers when compared to cotton fibers. Similarly, the water absorption values in the hemp blends are progressively increasing as the fiber ratio increases. The RH_75 sample has the maximum water absorption value (187.59%), whereas the RH_25 sample has the lowest (160.04%). The direct absorption of water molecules into the hydroxyl groups of the exterior surface and amorphous regions occurs extremely quickly, whereas indirect absorption in the interior surface voids and crystallites occurs comparatively slowly.[47] Thus, it can be said that the higher water absorption results of RH samples in comparison to RC and RF samples are consistent because hemp absorbs more water since the crystallinity of hemp fiber (34%)[43] is less than that of the other two fibers: cotton (87%)[48] and flax, as stated above.

Table 3
Water absorption capacity test results

Paper code	Water absorption ± [SD] (%)
R	171.35 ± 9.01
RC_25	133.24 ± 5.56
RC_50	116.50 ± 6.36
RC_75	105.94 ± 7.69
RF_25	150.91 ± 8.13
RF_50	151.92 ± 7.99
RF_75	185.56 ± 11.13
RH_25	160.04 ± 23.28
RH_50	168.95 ± 18.62
RH_75	187.59 ± 6.93

Table 4
Tensile strength and tensile index results of the paper samples

Paper code	Tensile strength ± [SD] (kN/m)	Tensile index ± [SD] (Nm/g)
R	5.51 ± 0.63	14.77 ± 0.19
RC_25	6.39 ± 0.64	25.79 ± 9.76
RC_50	7.85 ± 0.72	36.82 ± 3.55
RC_75	8.10 ± 0.29	49.08 ± 4.32
RF_25	8.90 ± 1.57	35.28 ± 4.11
RF_50	7.40 ± 0.43	34.13 ± 1.59
RF_75	5.97 ± 0.59	32.65 ± 3.31
RH_25	7.08 ± 0.51	28.89 ± 2.07
RH_50	5.31 ± 0.48	25.29 ± 2.29
RH_75	3.35 ± 0.25	24.82 ± 0.75

Tensile test results

In order to account for differences in basis weight associated with fiber type and reinforcement ratio, tensile strength results are normalized and evaluated in terms of tensile index (Table 4). A discernible enhancement in tensile index is observed upon comparing the values of normalized data between R samples and blend papers, indicating a significant increase in the paper's tensile index with the incorporation of textile fibers into the pulp.

In the assessment of the data categorized by fiber type, it becomes apparent that increasing the percentage of cotton fiber in the blend samples positively influences tensile strength, while the reverse is observed in the case of flax and hemp samples. It is known that enhanced mechanical properties can be achieved in fibers with increased cellulose content and decreased microfibrillar angle.[46] In terms of cotton, the strength is determined more specifically by the stiffness of its cellulose chains, highly fibrillar and crystalline structure, and substantial intermolecular and intramolecular hydrogen bonding.[45] This phenomenon therefore explains the direct relationship between the tensile strength and the ratio of cotton fiber in the paper. The superior tensile strength and tensile index exhibited by the RC_75 (8.1 kN/m and 49.08 Nm/g, respectively) are attributed to its elevated cellulose content exceeding 90% and a crystallinity range of 71-73%.[50,51] However, all three samples with differing cotton fiber ratios (25 to 75%) result in higher tensile strength and tensile index values than those of R samples.

A higher cellulose amount combined with lower lignin content in the biomass leads to greater paper strength. Non-wood biomass contains less lignin than wood (the lignin content of wood is 18-25%), allowing milder pulping conditions and thus reducing energy and resource use in papermaking. High hemicellulose content hinders cellulose processing and lowers paper strength, brightness, and opacity.[34]

In addition to crystallinity and cellulose content, fiber dimensions are also important in determining the mechanical properties. Cotton fibers are shorter and thinner than bask fibers such as flax and hemp.[52] At the same time, their flexibility ratio, calculated by the ratio of the fiber lumen diameter to the fiber diameter, is lower, thus allowing them to be distributed homogeneously within the paper structure, which makes a positive contribution to the mechanical properties.

On the other hand, the RF_25 sample has the greatest tensile strength and tensile index values (8.9 kN/m and 35.28 Nm/g, respectively) among the flax samples, indicating that adding a modest quantity of flax fiber boosts the strength significantly because it disperses more evenly into the waste pulp and binders; however, adding too much flax fiber causes the strength to decline due to the undesired fiber entanglements. The situation for hemp is similar to that of flax. Both fibers have comparatively lower cellulose ratios (75-80%) than cotton (90%)[43,44] and these fibers are longer in length and stiffer, which may result in irregular fiber distribution and thus nonhomogeneous load distribution, leading to damage under lower forces. Furthermore, hemp fiber's low processability adds drawbacks, too.

The tensile energy absorption and normalized tensile energy absorption index values clearly demonstrate the effect of fiber type and reinforcement ratio on the energy dissipation capability of recycled paper (Table 5).

Table 5
Tensile energy absorption and tensile energy absorption index results of the paper samples

Paper code	Tensile energy absorption ± [SD] (J/m^2)	Tensile energy absorption index ± [SD] (J/g)
R	111.61 ± 27.51	0.30 ± 0.05
RC_25	294.63 ± 22.81	1.37 ± 0.21
RC_50	303.36 ± 90.89	1.42 ± 0.40
RC_75	513.98 ± 27.18	3.11 ± 0.25
RF_25	310.76 ± 77.74	1.25 ± 0.27
RF_50	257.25 ± 34.20	1.19 ± 0.15
RF_75	180.75 ± 46.86	1.17 ± 0.28
RH_25	202.41 ± 70.19	0.83 ± 0.29
RH_50	149.87 ± 40.84	0.69 ± 0.22
RH_75	84.16 ± 9.98	0.62 ± 0.05

The reference sample (R) exhibits a low TEA of 111.61 ± 27.51 J/m² and a TEA index of 0.30 ± 0.05 J/g, indicating limited energy absorption capacity. Cotton-reinforced papers show a pronounced and progressive improvement with increasing fiber content, with TEA index values rising from 1.37 ± 0.21 J/g (RC_25) and 1.42 ± 0.40 J/g (RC_50) to a maximum of 3.11 ± 0.25 J/g for RC_75, representing more than a tenfold increase compared to the R sample. Flax-reinforced samples reach their highest normalized performance at low reinforcement levels, with RF_25 exhibiting a TEA index of 1.25 ± 0.27 J/g; further increases in flax content led to a gradual decrease to 1.19 ± 0.15 J/g (RF_50) and 1.17 ± 0.28 J/g (RF_75), likely due to fiber stiffness and dispersion limitations. Hemp-reinforced papers show the lowest normalized energy absorption, with TEA index values decreasing from 0.83 ± 0.29 J/g (RH_25) to 0.62 ± 0.05 J/g (RH_75), reflecting the limited contribution of hemp fibers to crack-bridging and plastic deformation mechanisms. Overall, the normalized results confirm that cotton fibers significantly enhance the intrinsic energy absorption performance of recycled paper, whereas flax and hemp fibers exhibit optimal effectiveness only at lower reinforcement ratios.

TEA values, determined from the area under the force–elongation curves[53] (Fig. 5) and listed in Table 5, also show a clear ranking among the samples. The lowest energy absorption is observed for the reference paper (R), followed by hemp- (RH) and flax-reinforced (RF) papers, while cotton-reinforced samples (RC) exhibit the highest TEA values.

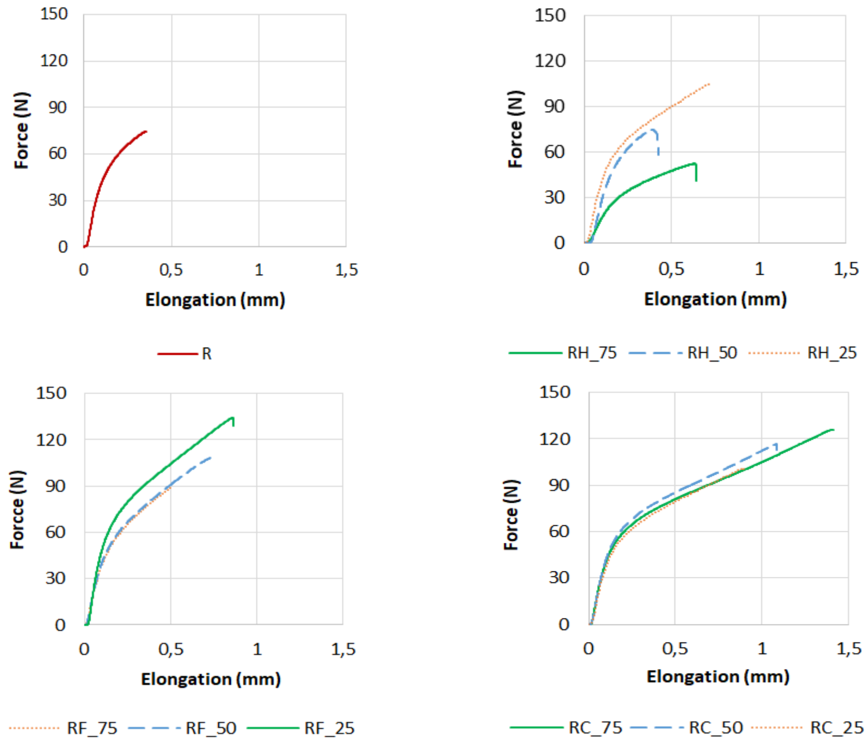

Figure 5: Force-elongation curves of R, RH, RF, and RC samples

CONCLUSION

In the course of this study, varying proportions (25-75% by weight) of waste cotton, flax, and hemp fibers were incorporated into recycled paper pulp to investigate the influence of these fibers on the paper properties. The study's findings demonstrate that, regardless of the raw material type, textile fiber reinforcement contributes to the mechanical properties of papers made from recycled pulp. Normalized tensile parameters reveal that cotton fibers provide the most effective reinforcement among the investigated fiber types. Papers reinforced with cotton (RC) exhibited a continuous increase in tensile index with increasing fiber content, which is attributed to the high cellulose content, high crystallinity, and favorable fibrillar structure of cotton fibers that promote strong inter-fiber bonding within the paper network. In contrast, flax and hemp fibers improved tensile performance only at lower reinforcement levels, while higher additions led to a decline in normalized mechanical properties due to non-uniform fiber dispersion and increased structural heterogeneity. The remarkable findings reveal that RC_75 has the highest tensile index (49.08 Nm/g) and tensile energy absorption index (3.11 J/g).

In conclusion, the study's outcomes hold the potential to enhance solid waste management by repurposing the substantial cellulose-containing waste generated by the textile industry. Additionally, it introduces an alternative raw material to the paper industry, alleviating the necessity for planting a considerable number of trees annually dedicated solely to paper production. However, although production waste, including raw textiles, has more potential to be utilized as raw materials for papermaking with fewer preparation steps, the post-consumer textile waste may require additional processing steps, such as removing dyes and chemicals or separating synthetic fibers or accessories, which can be complex, energy-intensive, and costly, making scaling more difficult. Therefore, ensuring consistent quality of the resulting paper products can be challenging and should be studied in detail, particularly when handling post-consumer waste. The handmade papers crafted within the purview of this research, featuring pioneering and original content, are anticipated to find application in artistic realms such as watercolor and calligraphy. Additionally, they can be sustainable alternatives for luxury and eco-conscious packaging, providing biodegradable and recyclable options over traditional plastic or non-recyclable materials. Their versatility extends to office supplies, including notebooks, writing pads, envelopes, and business cards, as well as products like garment tags, sustainable shopping bags, and labels for the textile industry.

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