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Eco-Friendly Solutions to Enhance the Mechanical Properties of Handmade Recycling Papers

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Abstract: This study examines the behaviour of mechanical properties of handmade recycled paper which is improved by adding waste yarn and rubber latex. The main objectives of this research are to enhance the tensile strength, shear strength, and water resistance by identifying the most effective proportions for blending wastepaper, waste yarn, and latex. The study utilizes conventional recycling techniques enhanced with these materials, leading to substantial enhancements. The experimental results demonstrate that adding waste yarn into the wastepaper enhances the tensile strength from 1.21 MPa to 6.08 MPa when the yarn content is increased. Shear strength reaches a maximum of 1.65 MPa when the waste yarn content is 40%. Incorporating rubber latex to the wastepaper boosts water resistance and further enhances the strength of the paper. The tensile strength of recycled paper increased from 1.21 MPa to 6.08 MPa with waste yarn addition, while shear strength reached a maximum of 1.65 MPa at 40% yarn content. Incorporation of natural rubber latex further enhanced tensile strength up to 17.42 MPa and reduced water absorptivity by approximately 65%. These improvements indicate that the developed recycled paper is suitable for packaging and utility applications requiring enhanced strength and moisture resistance. The research findings reveal that finest combinations of waste yarn and rubber latex can greatly improve the mechanical properties of handmade recycled paper. Based on these observations, the property enhanced recycled papers are highly suitable for any industrial and domestic applications and have a positive impact on the conservation of the environment. It also has the impact of reusing waste materials to avoid wastage in the manufacture of new papers which can put pressure on natural resources and thereby help to preserve natural resources and decrease landfill waste. Due to the massive consumption of paper in the world, these results offer an eco-friendly solution to ensure environmental protection.

Keywords: Eco-friendly, Handmade paper, Recycling, Rubber latex, Wastepaper, Waste yarn

1. Introduction

Recycled paper has been used worldwide in the production of fertilizers and value-added products in the past decades [1]. The handmade paper industry which uses the wastepaper for their products marks a progressive shift towards sustainable and environmentally conscious practices. Wastepaper creates landfills leading to environmental degradation. It can be reused and utilized in the production of handmade paper. It significantly decreases the environmental burden associated with landfill disposal. This approach enhances the eco-friendliness of the paper product. The primary advantage of incorporating wastepaper into handmade paper production is that the industry reduces the usage of fresh wood pulp. This helps to reduce deforestation and enhance the conservation of forests, essential for biodiversity. The utilization of wastepaper in the handmade paper industry contributes to energy savings. Recycled paper processing normally requires less energy compared to the production of paper from virgin pulp. Recycling wastepaper is more cost-effective than processing new raw materials for paper making. This economic advantage contributes to the overall sustainability of the handmade paper production process. Papers used for packaging, utility and industrial applications typically require enhanced tensile and shear strength, along with moderate water resistance to ensure durability during handling and service. The proposed approach aims to achieve these target properties using waste-derived materials, thereby improving the functional performance of handmade recycled paper while maintaining environmental sustainability.

In Sri Lanka, the paper recycling process is usually done by using the conventional methods. The handmade paper making process consists of mixing chips of used paper with chemicals and water and then chopping up the mixture and heating. This chopped mixture is known as the

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pulp. Then the filtering process is done which helps to remove unnecessary particles that may still be in the mixture. Then the pulp is used to make recycled paper. When considering the quality of their handmade paper, it is not sufficient for commercial products since its strength, water resistance, and surface quality are low compared to the normal paper products. Fiber consumption is increasing continuously, and it will be increasing further in future [2]. According to the available data, the average global textile waste has doubled since rapid change of fashions. In addition, this rapid increase of waste fabric is a result of issues of improper handling of textiles and throw away culture. Textile waste is becoming a major contributor to environmental pollution.

Industrial textile waste mainly happens during manufacturing process. In addition, the textile consumer waste is generated when discarded textile materials complete their service life. The waste management of apparel industry is an important task since only 20% of cloth waste is reused and recycled while the remainder is mainly used for landfilling. This will lead to energy wastage and has a harmful impact on the environment [3]. To strengthen the circular economy, solid waste must be reused or recycled. A substantial amount of apparel waste is generated while manufacturing processes of knitting/weaving, spinning, dyeing, apparel making, and finishing [4]. Approximate textile waste generation in 2024 is 92 million tons. In Bangladesh, more than 500,000 tons of textile waste is generated from the apparel industry. Among these, 250,000 tons can be totally recycled to earn 100 million USD. The global textile waste annually increased and estimated increase is 60% each year between 2015 and 2030 [5]. Therefore, the usage of textile waste in a proper application is an important task. The papermaking process entails creating a watery mixture of cellulose fibers, usually obtained from wood, and then generating a thin layer of dry fibers by filtering against a suitable screen. The process of pulping wood involves the use of blunt blades to cut and bruise the cellulose fibers, which are then beaten in water. The fiber length and fibrillation are influenced by the magnitude and duration of beating, sometimes assisted by chemical substances. The pulp undergoes a cleaning process and is then diluted to make paper stock. This paper stock is further transformed into paper by filtering, using either a horizontal screen (Fourdrinier machine) or a cylindrical screen (cylinder machine). The fiber web is constantly removed for additional processing, including optional coating treatments to increase look and printability [6]. Polymer latices are used in three main processes in papermaking.

In the mechanical technique for generating recycled papers using latex, there are three primary uses of latices in paper technology: beater addition (adding latices during beater stage), saturation of dried paper (infuse dried paper with a latex), and surface coating of paper (latex addition affect to the surface quality of the paper). The addition of latex may result in changes to characteristics such as strength, durability, and tear strength of the paper [7]. The amount of latex added to the paper may influence the mechanical properties, including considerations for polymer film-forming temperatures. The natural rubber latex enhances the tensile strength of recycled paper by establishing a cohesive matrix that efficiently binds fibers [8]. The constant concerns with the issues of the environment add pressure to look for more effective ways of waste management, especially in the textile and paper sectors. Waste yarn, a scrap material widely used in the textile industry, mostly ends up in landfills or is burned immediately after use, thus causing pollution. Synthetic fibers cannot degrade, and hence they remain in the environment for a long time before finding their way into water and soil resources [9]. In the same way, when used paper items are improperly disposed of, they find their way into the waste disposal system while creating massive landfill wastes. When these materials end up in landfills or other sources of environmental disposal, more than just the space is wasted; the release of chemicals, microplastics, and greenhouse gases are also encouraged. In the long run, such types of wastes cause grievous harm to the balance of ecology, affecting the biodiversity, water resources and the physical condition of the soil [10]. However, due to the constant need for more paper products that are continuously being produced, deforestation is promoted, threatening the loss of biodiversity and the interruption of carbon-storing abilities, all of which contribute to climate change.

On the other hand, the utilization of waste yarn and paper to create new products of better quality helps in addressing these environmental issues. Recycling waste yarn into paper products significantly reduces the volume of solid waste sent to landfills. It is addressing a major global waste management challenge, particularly in developed countries. This process not only helps in the avoidance of the emission of pollutants but also helps in saving natural resources as there is less dependency on virgin materials [11]. The environmental benefits are twofold: first, it reduces the negative impact of discarded yarn and paper products on the environment; second, it helps reduce the level of environmental pollution caused by using new products in industries that emit pollutants and consume energy in the production processes [12]. The current work was undertaken to utilize wastepaper, waste yarn, and natural rubber latex as a raw material for handmade paper manufacturing. Handmade papers were prepared from 100% waste papers, blend with waste papers with waste yarn in different weight percentages and add natural rubber latex to waste papers and waste yarn mixtures [13]. The mechanical properties of the prepared handmade papers were compared with reference handmade papers manufactured with 100% waste papers that are traditionally used to produce commercial purposes.

2. Materials and Method

The investigation begins with an in-depth examination of the paper recycling process. Initially, used and discarded papers were collected as raw materials. The process involved several essential stages, beginning with pulping, where the papers were mixed with water and chemicals such as rosin and alum [14]. This was followed by paper manufacture utilizing the dipping process and pressing to remove surplus water according to Figure 1.

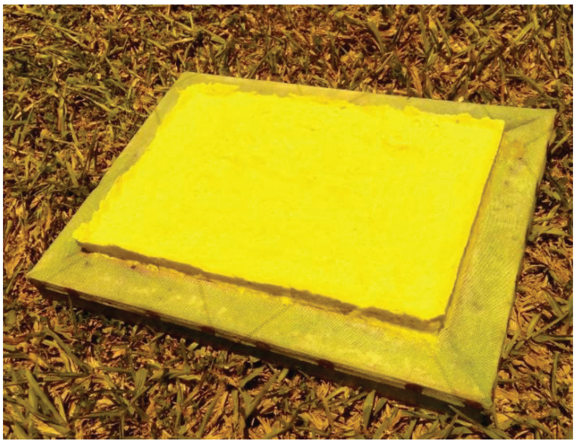

Figure 1 - Test specimen

The ensuing processes included drying, ironing, and trimming. Innovations in the technique entailed adding waste yarn, sourced from garment manufacturers. Additionally, improvements were made to the drying process by introducing dehumidification instead of natural drying. Ironing was substituted by rolling using a diamond-cut roller to enhance shape and surface quality. The first set of experiments were done by changing the amount of yarn. The wastepaper quantity and yarn quantity were mixed as shown in Table 1. Rosin and alum quantity were kept constant for all samples. Then, the mechanical properties such as tensile strength, shear strength, and water absorptivity of papers were checked.

Table 1 - Composition of wastepaper and yarn for the first set of experiments

Sample number	Wastepaper percentage (%)	Yarn percentage (%)
Y01	100	0
Y02	90	10
Y03	85	15
Y04	70	30
Y05	60	40
Y06	50	50
Y07	40	60

A tensile testing machine was used to measure the tensile strength of samples under the standard conditions of 23 °C temperature and 50% relative humidity. Six paper specimens were tested and get the average value for each sample size. The shear strength of the papers was measured using basic configuration of strength testing measure. First, the paper samples were cut into small strips. Then one end of the sample was attached to a weight measuring bucket and the other end was kept fixed. Then small weights were added to the weight measuring bucket till the paper sample brakes [15]. Then the shear strength was calculated using the value of added weights. The water absorptivity of the paper samples was measured by a standard Cobb tester. The excess water from the wetted paper sample was removed by rolling a 10 kg weight hand roller without applying additional pressure. The difference in weight of the paper sample after and before wetting was used to calculate the water absorptivity value [16]. Then the second set of experiments were conducted based on the results of the first set of experiments. The composition of sample number Y05 has been selected as the best wastepaper and yarn mixture based on the tensile strength, shear strength, and water absorptivity properties. The tensile strength of the paper samples increased with increasing the amount of yarn added. However, the shear strength increased from sample number Y01 to sample number Y05. The maximum shear strength showed for Y05 sample. Shear strength drops after that although yarn quantity increased. Water absorptivity showed nearly the same value for all samples except Y01. Based on those results, Y05 composition was selected for the second set of experiments since it has high tensile strength as well as highest shear strength.

The selection of sample Y05 was based on a multi-criteria assessment considering tensile strength, shear strength, and water absorptivity. Although tensile strength continued to increase with higher yarn content, the maximum shear strength was observed at 40% yarn addition, while water absorptivity remained within acceptable limits. Therefore, Y05 was selected as the optimal composition for further latex modification. The second set of experiments was done by adding the latex at the pulping stage to sample number Y05 composition. Sample number Y05 consists of 60% wastepaper and 40% yarn. The latex was mixed to the wastepaper and yarn mixture as shown in Table 2. Added latex volume was limited to 40 ml due to practical difficulties. When the latex volume is increased, it is difficult to separate paper layers from the mold. Then, the mechanical properties such as tensile strength, shear strength, and water absorptivity of the latex mixed papers were checked.

Table 2 - Latex quantity added to samples

Sample number	Latex volume (ml)
L01	0
L02	10
L03	20
L04	30
L05	40

3. Results and Discussion

The improvement in tensile strength with increasing waste yarn content can be attributed to the reinforcing role of textile fibers within the cellulose matrix. These fibers act as stress-bearing components that enhance load transfer and restrict micro-crack initiation and propagation. At moderate yarn content, improved fiber dispersion and bonding enhance the integrity of the matrix [17]. However, beyond the optimal yarn content, fiber agglomeration and insufficient inter-fiber bonding reduce matrix continuity, resulting in diminished shear performance. The incorporation of natural rubber latex further enhances mechanical properties by forming a continuous polymeric film around cellulose and yarn fibers. This film improves interfacial adhesion through physical entanglement and hydrogen bonding, leading to improved stress distribution under tensile and shear loading. In addition, the hydrophobic nature of latex partially seals pore structures within the paper matrix, reducing capillary water penetration and significantly improving water resistance. The mechanical performance obtained in this study compares favourably with previously reported results. Notable improvements in tensile strength have been observed in recycled paper reinforced with cotton spinning waste, along with enhanced mechanical performance and reduced water absorption in latex-bonded recycled paper composites [13–14]. The tensile strength achieved in the present study, particularly with latex incorporation, exceeds many reported values, confirming the effectiveness of combining waste yarn reinforcement with natural rubber latex modification. From an economic and energy perspective, the proposed recycling approach offers clear advantages over conventional virgin pulp-based paper production. The use of wastepaper and waste yarn significantly reduces raw material costs, while recycled paper manufacturing typically requires substantially less energy than virgin pulp processing. Literature reports indicate that recycling-based paper production can reduce energy consumption by up to 50% [18]. Additionally, the avoidance of intensive chemical pulping further contributes to lower energy demand, supporting the sustainability of the proposed method.

3.1 Tensile Strength of Wastepaper and Yarn Mixed Paper

The addition of waste yarn to handmade recycled paper significantly enhances its tensile strength as shown in Figure 2. When paper contains no yarn, it has a baseline tensile strength of 1.21 MPa. However, when yarn is added to the paper, its tensile strength steadily increases. With a yarn percentage of 10%, the tensile strength increases to 1.53 MPa, suggesting a moderate improvement. The trend continues, as the inclusion of 15% yarn results in a tensile strength of 2.32 MPa, while 30% yarn content yields a tensile strength of 3.50 MPa. The greatest improvements are shown when using greater amounts of yarn, with a tensile strength of 5.42 MPa achieved at a yarn content of 40%, and a slightly higher strength of 5.98 MPa achieved at a yarn content of 50%. The highest measured tensile strength of 6.08 MPa is achieved when the yarn content is at 60%, demonstrating an almost fivefold increase compared to the initial value. The small standard deviation values observed in these measures confirm the consistency and dependability of the data. The data unequivocally illustrates that incorporating waste yarn into recycled paper improves its structural integrity, resulting in a substantial increase in strength and durability.

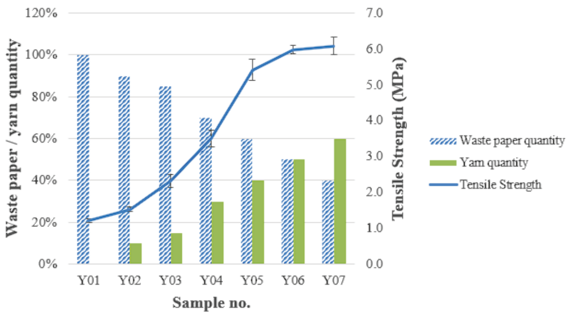

Figure 2 - Tensile strength of wastepaper and yarn mixed paper

3.2 Shear Strength of Wastepaper and Yarn Mixed Paper

The inclusion of waste yarn in recycled paper also enhances its shear strength, but the pattern of enhancement varies from that seen in tensile strength as shown in Figure 3. At first, the shear strength of the paper rises from a starting point of 0.45 MPa when there is no yarn present, to 0.65 MPa when the yarn content is 10%. Further gains are found at 15% yarn content, with the shear strength reaching 0.85 MPa. A considerable gain is noted at 30% yarn content, when the shear strength peaks at 1.04 MPa. However, with 40% yarn content, the shear strength dramatically increases to 1.65 MPa, showing an ideal concentration for increasing this feature. Beyond this limit, at 50% and 60% yarn content, the shear strength declines to 0.88 MPa and 0.66 MPa, respectively. These decreases show that too high yarn content may disturb the cohesiveness of the paper matrix, resulting in lower shear strength. The constantly modest standard deviations underline the trustworthiness of these results. Overall, the ideal yarn percentage for maximum shear strength seems to be approximately 30-40%, where the advantages are most obvious.

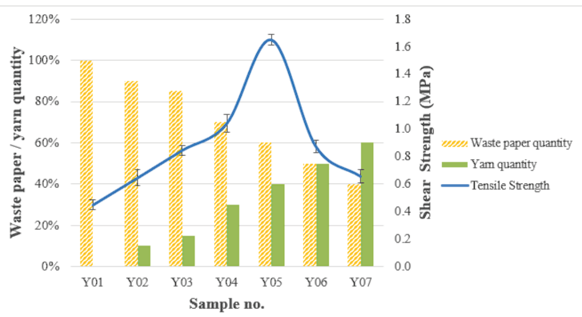

Figure 3 - Shear strength of wastepaper and yarn mixed paper

The observed improvement in tensile strength can be attributed to the inherent tensile strength and length of the waste yarn fibers, which act as reinforcement elements within the cellulose matrix. These fibers bridge adjacent cellulose fibers and enhance load transfer efficiency. In shear loading, optimal yarn content improves resistance to inter-fiber sliding; however, excessive yarn addition leads to poor dispersion and reduced fiber bonding, resulting in a decline in shear strength.

3.3 Water Absorptivity of Wastepaper and Yarn Mixed Paper

Water absorptivity, an important feature for recycled paper used in numerous applications, demonstrates small variations with the insertion of waste yarn. With reference to Figure 4, the baseline of water absorptivity for paper without any yarn is 0.19 mg/m². With the addition of 10% yarn, this improves to 0.24 mg/m², and further to 0.25 mg/m² with 15% yarn content. The greatest absorptivity of 0.27 mg/m² is measured at 30% yarn content, implying greater porosity and surface area owing to the presence of yarn fibers. However, after this threshold, water absorptivity continues to drop, with 40% yarn content displaying a value of 0.26 mg/m², and both 50% and 60% yarn content producing absorptivity values of 0.23 mg/m².

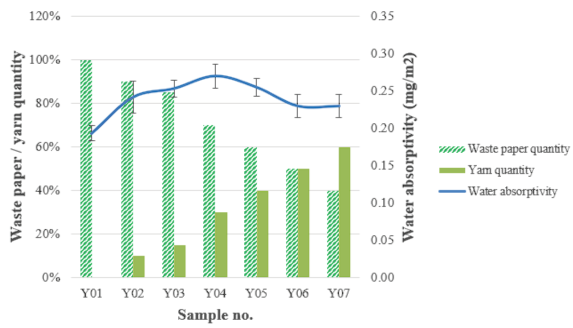

Figure 4 - Water absorptivity of wastepaper and yarn mixed paper

These data demonstrate that although moderate yarn concentration promotes water absorptivity by increasing the paper's porosity, greater yarn levels may impair this attribute by filling the matrix and restricting water penetration. The low standard deviations indicate the dependability of these measures. Thus, keeping a balanced yarn content is vital for maximizing water absorptivity and mechanical qualities.

3.4 Tensile Strength of Latex Mixed Wastepaper

The use of rubber latex greatly enhances the tensile strength of handmade recycled paper. The first control sample, which included 0 ml of latex, had a tensile strength of 5.42 MPa. With the addition of latex, the tensile strength shows a clear improvement: 9.47 MPa with 10 ml, 11.18 MPa with 20 ml, 12.42 MPa with 30 ml, and a significant 17.42 MPa with 40 ml (see Figure 5). This demonstrates a significant improvement of 221% of tensile strength compared to the first measurement, emphasizing the efficient contribution of latex in strengthening the paper fibers. The reliability of these findings is shown by the small standard deviation, indicating consistent progress. The latex presumably creates a cohesive structure that improves the adhesion between fibers, hence enhancing the paper's tensile strength.

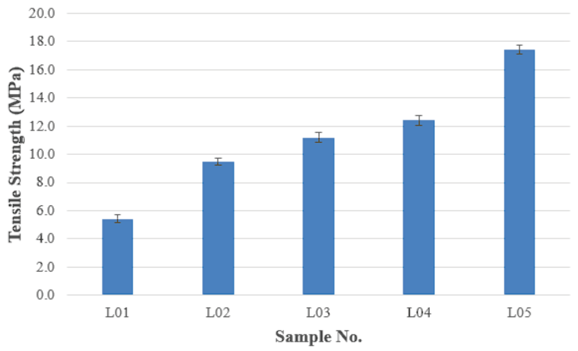

Figure 5 - Tensile strength of latex mixed wastepaper

3.5 Shear Strength of Latex Mixed Wastepaper

Incorporating rubber latex into the recycled paper results in a significant enhancement in its shear strength as shown in Figure 6. The control sample has a shear strength of 1.65 MPa. The strength of the material rises to 2.17 MPa when 10 ml of latex is added, 3.85 MPa with 20 ml, 4.25 MPa with 30 ml, and 4.55 MPa with 40 ml of latex.

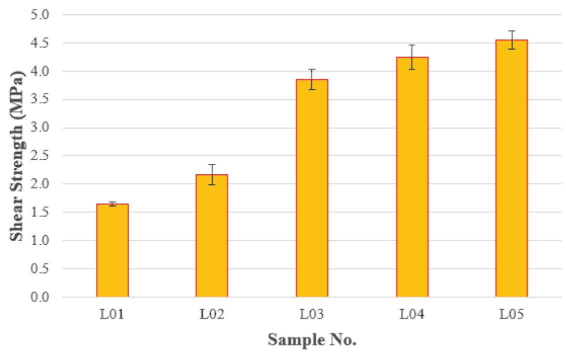

Figure 6 - Shear strength of latex mixed wastepaper

The augmentation reaches its peak at 40 ml, indicating a 176% increment of shear strength over the control sample. The continuous improvement, supported by the comparatively low standard deviation, indicates that latex efficiently enhances the shear strength by improving the adhesion between paper fibers and the included yarn. The reinforced matrix aids in dispersing applied shear stresses more effectively, thereby reducing fiber slippage and failure under stress.

3.6 Water Absorptivity of Latex Mixed Wastepaper

Water absorptivity of the handmade recycled paper reduces with the addition of rubber latex. As shown in Figure 7, the control sample displays a water absorptivity of 0.26 MPa. With the gradual addition of latex, the water absorptivity values decline to 0.20 MPa (10 ml), 0.18 MPa (20 ml), 0.12 MPa (30 ml), and 0.09 MPa (40 ml). This large reduction, notably the 65% decrease at the 40 ml level, might be ascribed to the hydrophobic characteristic of latex. The rubber latex produces a barrier that inhibits the paper's capacity to absorb water, boosting its endurance in damp settings.

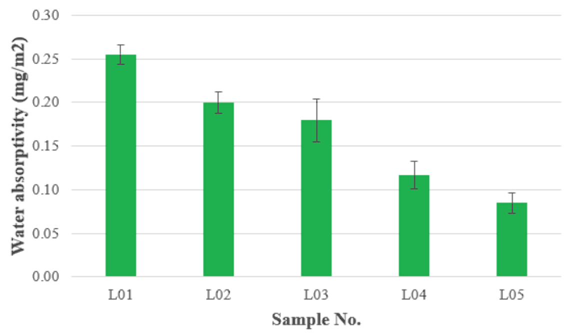

Figure 7 - Water absorptivity of latex mixed wastepaper

The uniform standard deviation shows that this quality is consistently enhanced across multiple samples, making the recycled paper more appropriate for applications where water resistance is crucial. The reduction in water absorptivity with increasing latex content is attributed to the formation of a hydrophobic polymer film within the paper structure. This film partially seals pores and reduces capillary pathways, limiting water penetration. When latex content increases, pore connectivity decreases, resulting in improved water resistance. The study confirms that waste yarn and natural rubber latex can be effectively used to enhance the mechanical and physical properties of handmade recycled paper. Significant improvements in tensile strength, shear strength, and water resistance were achieved using an optimized material composition. The developed paper demonstrates potential for packaging and utility applications while contributing to waste reduction and sustainable material utilization. These results demonstrate that recycled papers have the appropriate characteristics for industrial and domestic use. Since paper is in high demand across the world, these recycled options serve as a perfect replacement for new paper production. Consequently, opting for recycled papers will immensely benefit the environment since they reduce the utilization of virgin paper pulp and mitigate the associated ecological impacts. Recycling of paper is one of the main environmental conservation activities, it helps in reducing the use of virgin timber, thus helping in the conservation of forests and endangered species. It also reduces landfill waste which releases methane during decomposition while using less energy and water than new paper production [18]. In addition, the reuse of paper also reduces air and water pollution because there will be fewer chemical processes involved. Recycling of paper leads to a reduction in the use of natural resources and energy in the manufacture of paper, hence a reduction in the emission of greenhouse gases and thus leads to the creation of a more environmentally friendly world [18]. Not only that, the use of waste yarn in the preparation of recycled paper can go a long way in the effort to ensure that the environment is protected, and textile waste is well managed. In most cases, waste yarn generated by the textile and apparel industries is deposited in landfills in which there is generation of methane and other pollutants. However, diverting this yarn into the paper manufacturing process not only helps to avoid virgin paper pulp but also aids in getting rid of textile waste buildup. This greatly cuts down on the disposal of waste in landfills, minimizes the utilization of resources by reducing the need for raw materials, and is part of the circular economy as it restyles the worn-out materials and sustains their usage, consequently decreasing the environmental effects. Therefore, incorporating waste yarn in paper manufacturing increases the paper quality while enhancing major efforts at environmental protection.

4. Conclusions

This study demonstrates that the mechanical and physical properties of handmade recycled paper can be significantly enhanced by incorporating waste yarn and natural rubber latex. Waste yarn reinforcement improves tensile and shear strength by enhancing fiber bridging and load transfer mechanisms within the cellulose matrix, while natural rubber latex further strengthens the paper by improving inter-fiber adhesion and reducing porosity. The tensile strength increased by more than 5 times compared to conventional handmade recycled paper, while shear strength showed a substantial improvement at optimal yarn content. Additionally, the tensile strength of the recycled paper increased to 17.42 MPa from 1.21 MPa, with the inclusion of 60% waste yarn and 40 mL of rubber latex. At the same time, shear strength increased up to 4.55 MPa. The addition of latex reduced water absorptivity by up to 65% (from 0.26 mg/m^2 to 0.09 mg/m^2), attributed to the hydrophobic nature of the polymer film formed within the paper structure. Beyond performance enhancement, the proposed method offers strong environmental and economic benefits by reducing textile waste, lowering dependence on virgin pulp, and decreasing energy consumption. These findings confirm the suitability of waste yarn and rubber latex-modified recycled paper for industrial and domestic applications and strongly support circular economy and sustainable manufacturing practices.

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