

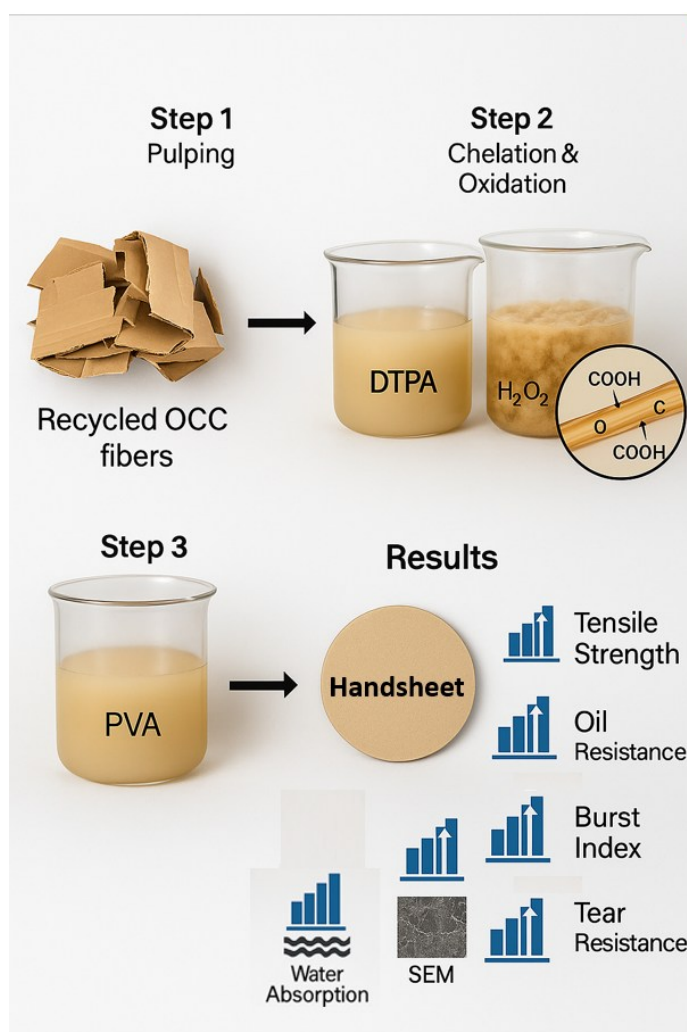
The Effect of OCC Fibers Surface Modification and Polyvinyl Alcohol on the Properties of Test Liner Paper

Mehran Parastar ^a, Nouredin Nazarnezhad ^{b,*} and Qasim Asadpour ^c

* Corresponding author: nazarnezhad91@gmail.com

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GRAPHICAL ABSTRACT



The Effect of OCC Fibers Surface Modification and Polyvinyl Alcohol on the Properties of Test Liner Paper

Mehran Parastar ^a, Nouredin Nazarnezhad ^{b,*} and Qasim Asadpour ^c

One of the most important properties of paper is its mechanical strength. The recycled paper industry faces challenges related to fiber strength in old corrugated container (OCC) products. This study investigated the efficacy of polyvinyl alcohol (PVOH) as reinforcing agent when OCC fibers were modified with oxidative treatment by using hydrogen peroxide. The surface oxidation introduced carboxyl groups on the cellulosic chains of the OCC fibers, and PVOH had significant effect on the interaction between fibers and carboxyl groups. Results showed that PVOH-treated samples, especially the oxidized samples of the OCC fibers, exhibited significant improvement in tensile and burst strength compared to untreated samples. Scanning electron microscopy (SEM) showed that the oxidative modification of OCC fibers led to a decrease in porosity and an increase in the connection between fibers, and this process also led to an increase in the adhesion of PVOH and an improvement of its bonding. In addition, the treated samples showed higher resistance to fat permeation, which is a key characteristic for industrial packaging applications. This approach indicated the synergistic benefit of combining the PVOH and oxidized OCC fibers to boost the formation and barrier properties of the recycled papers. This method also provided an effective and eco-friendly solution to improving the recycled papers' quality.

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Keywords: Surface modification; Polyvinyl alcohol; Liner paper; Water absorption; Old corrugated container

Contact information: a: PhD student of Wood Industry and Cellulose Products, Sari University of Agricultural Sciences and Natural Resources; b: Associate Professor, Department of Wood and Paper Science, Sari University of Agricultural Sciences and Natural Resources; c: Associate Professor, Department of Wood and Paper Science, Sari University of Agricultural Sciences and Natural Resources; * Corresponding author: nazarnezhad91@gmail.com

INTRODUCTION

The use of recycled fibers for paper production has become essential due to the scarcity of wood sources, limited availability of virgin fibers, environmental concerns, and population growth. Among the various types of wastepaper, old corrugated containers (OCC) represent the most significant category for recycling in terms of recovery percentage and tonnage. Additionally, OCC is one of the most cost-effective raw materials in the pulp and paper industry (Li *et al.* 2023). According to the Food and Agriculture Organization of the United Nations (FAO), the global production of paper and cardboard reached 417 million tons in 2022, of which 244 million tons (approximately 58%) were recycled. In comparison, the production in 2020 was 400 million tons, with recycled paper production reaching 228 million tons (FAO 2023).

Despite the increasing emphasis on recycling, the utilization of wastepaper poses significant challenges for paper and paperboard manufacturers. The main limitation is the deterioration of fiber strength after multiple recycling processes. Recycled fibers experience considerable reductions in mechanical properties due to repeated drying and rewetting cycles (Pivnenko *et al.* 2015; Yılmaz and Gümüşkaya 2015). The reduction in tensile strength of chemical pulps after recycling has been reported to range between 10% and 70% (Wang *et al.* 2023). Furthermore, gradual fiber shortening and reduced bonding capability limit the number of recycling cycles for producing high-quality paper (Patrick 2011). Therefore, improving the strength and bonding properties of recycled paper is essential for expanding its applications and conserving raw material resources (Fu *et al.* 2022).

To overcome these limitations, surface modification and chemical treatments have been explored to enhance the bonding potential of recycled fibers. One promising strategy is oxidative surface modification. Oxidation using hydrogen peroxide (H_2O_2) is a widely studied chemical process that introduces carboxyl and carbonyl groups onto the cellulose fibers, enhancing their reactivity and bonding capabilities. Depending on reaction conditions, hydroxyl groups on cellulose chains are converted to aldehyde or carboxyl groups during oxidation. Oxidizers such as chlorine dioxide, ozone, and H_2O_2 can also be employed, with hydrogen peroxide being particularly attractive due to its chlorine-free nature and compatibility with both elemental chlorine-free (ECF) and totally chlorine-free (TCF) bleaching applications (Wen *et al.* 2019; Hasan *et al.* 2022). Hydrogen peroxide oxidation is typically performed under alkaline conditions, where pH significantly influences the formation of functional groups. Alkaline conditions favor the formation of carboxylic groups, which improve the strength and flexibility of fibers and, consequently, the paper properties (Barbosa *et al.* 2013; Fu *et al.* 2013; Martinsson *et al.* 2020). Oxidized cellulose fibers have found applications in diverse fields, including papermaking, textiles, and composites (Coseri *et al.* 2013). For instance, Li *et al.* (2020) demonstrated that hydrogen peroxide treatment increases the carboxyl content of fibers, resulting in improved bonding performance.

In addition to chemical modification, the use of strength additives represents another effective approach for improving recycled paper properties. Common additives include both natural and synthetic polymers such as polyvinyl alcohol (PVOH), cationic starch, and chitosan. Among these, PVOH stands out due to its low cost, hydrophilic nature, and ability to simultaneously improve dry and wet strength (Lee and Deng 2012). Although several fiber-surface modification strategies have been reported in the literature, such as reinforcement with TEMPO-oxidized nanocellulose (Indarti *et al.* 2023), many of these methods are limited by high cost, processing complexity, or poor drainage behavior. For example, Indarti *et al.* (2023) showed that TEMPO-oxidized nanocellulose significantly improved the tensile and tear strength of recycled papers but led to slower drainage and challenges for large-scale implementation. Hydrogen peroxide oxidation, on the other hand, can increase carbonyl group content and improve wet-web strength, although in some cases it may slightly reduce intrinsic fiber strength (Martinsson *et al.* 2022).

Building on these findings, the present study proposes a simple and scalable approach that combines mild hydrogen peroxide oxidation with a low-dosage PVOH treatment. The oxidation introduces carboxyl groups on fibre surfaces, which can form additional hydrogen bonds with the hydroxyl groups of PVOH, thereby improving the inter-fiber adhesion and enhancing both strength and barrier properties of recycled paper. This combined strategy mitigates the quality deterioration associated with recycled fibers

and promotes the production of high-performance, sustainable packaging materials with reduced dependence on virgin pulp. In the corrugated packaging industry, the concept of maintaining strength while reducing basis weight has long been an important consideration. According to the classical “Rule 41,” manufacturers are allowed to use lower grammages of linerboard provided that sufficient measures are taken to maintain the required strength properties (Gutmann *et al.* 1992). This regulation underscores the industrial importance of approaches such as surface oxidation and PVOH reinforcement, which can enhance fiber bonding and mechanical performance while enabling lighter and more resource-efficient paper products.

EXPERIMENTAL

Materials

OCC fibers were obtained from a wastepaper collection center. Polyvinyl alcohol (1.19 g/cm³ density, 72000 molar mass) was purchased from Sigma-Aldrich (St. Louis, MO). Hydrogen peroxide, sodium silicate, sodium hydroxide, and diethylenetriamine-pentaacetic acid (DTPA) were purchased from Merck & Co (USA).

Methods

OCC specimens were cut into 5 cm² pieces and soaked in water for 24 h, and then the fibers were obtained using a laboratory pulp disintegrator for 30 min. The resulting pulp was dried at room temperature. Then the moisture content was determined according to the TAPPI standard T 412 om 94 (TAPPI 2007).

Chelation process

The chelating agent DTPA was used to remove transition metal ions and thus prevent premature decomposition of hydrogen peroxide. The prepared OCC pulp was chelated under the conditions listed in Table 1 prior to the oxidative treatment.

Table 1. Pretreatment Conditions for Chelation

DTPA	Temperature	Time	Dryness percentage	pH
%	°C	min	%	
0.5	60	30	60	5-5.5

Oxidation treatment with hydrogen peroxide

The treatment conditions with hydrogen peroxide are summarized in Table 2. Initially, the prepared pulp was placed in a polyethylene bag. Then, sodium silicate and sodium hydroxide were dissolved in the required amount of distilled water and added to the pulp in the polyethylene bag, mixing thoroughly. In the next step, hydrogen peroxide (2%) was added to the chelated pulp suspension under alkaline conditions (pH $\approx$ 10) at room temperature (25 ± 2 °C) while stirring continuously to ensure uniform oxidation. The bag was placed in a warm water bath (Bain-marie) at 70 °C for 90 min. The pulp was kneaded every 15 min to ensure uniform treatment. After the treatment, the pulp was washed with distilled water to remove the chemicals.

Table 2. Treatment Conditions of OCC Pulp with Different Percentages of Hydrogen Peroxide

Dryness percentage (%)	Time (min)	pH	NaoH/H ₂ O ₂	Hydrogen peroxide (%)	Sodium silicate (%)	Temperature (°C)
10	90	10 - 11	0.8	0,0.5,1,2,3,4	3	70

Methylene blue adsorption method

The carboxyl group content of the oxidized pulp fibers was determined by the methylene blue adsorption method, as described by Fardim and Holmbom (2003). Approximately 0.5 g of pulp (90% moisture content) was mixed with 25 mL of a methylene blue solution and 25 mL of borate buffer. The suspension was gently stirred at 20 °C for 1 h to ensure complete dye adsorption, and then filtered. Subsequently, 10 mL of 0.1 N HCl was added to the filtrate, and the total volume was adjusted to 100 mL with distilled water. The concentration of methylene blue in the solution was measured spectrophotometrically at 664 nm using a calibration curve. The amount of unadsorbed (free) methylene blue was determined according to Eq. (1), and the difference between the initial and residual dye concentrations was used to calculate the carboxyl group content of the fibers.

$$\left(\frac{g}{mmol}\right) \text{ Carboxyl Groups} = \frac{7.5 - A \cdot 0.00313}{E} \quad (1)$$

In Eq. 1, *A* denotes the total amount of free methylene blue (mmol/ COOH) and *E* represents the dry weight of pulp sample (g)

Preparation of polyvinyl alcohol

To prepare the PVOH solution, first 3 g of solid PVOH powder was weighed using a digital scale with an accuracy of 0.01 g, then 100 mL of distilled water was added in a 300 mL beaker. Then, in order to make the solution, the beaker was placed on a magnetic stirrer with medium speed and heated at 60 °C. After the end of 60 min, PVOH dissolved in water, and the solution was brought to room temperature in the laboratory environment. Then it was added to the pulp suspension.

Handsheet production and analysis

To evaluate the strength characteristics and physical properties of the prepared pulp, laboratory handsheets were produced according to the TAPPI T 205 sp-02 standard. Handsheets with a basis weight of 120 g m⁻² were prepared using a standard sheet former. The required amount of dry pulp (2.4 g per sheet) was calculated based on the target basis weight. After sheet formation, polyvinyl alcohol (PVOH) was added to the fiber suspension prior to papermaking to obtain the modified samples. The wet sheets were placed between blotting papers and pressed manually for 7 minutes under a pressure of 4 kg cm⁻² to remove excess water. Subsequently, the pressed sheets were transferred to drying rings and air-dried under ambient laboratory conditions (approximately 23 °C and 50% relative humidity) for 24 h. This procedure ensured gradual drying and minimized sheet deformation.

The characteristics of the prepared papers were evaluated based on TAPPI standards, including tearing resistance (TAPPI 04 OM 414T, 2007), water absorption using the Cobb method (TAPPI 04om 441T), fat penetration resistance (TAPPI 99cm 507T),

tensile strength (TAPPI 01 OM 494T), and bursting resistance (TAPPI 02OM 403T). Additionally, the morphological structure of treated paper fibers was analyzed using a field emission scanning electron microscope (SEM), and the state of carboxyl groups on fiber surfaces before and after hydrogen peroxide treatment was examined through FTIR spectroscopy.

Statistical Analysis of Data

For the statistical analysis of this study, SPSS software was used. The data were analyzed as factorial experiments within a completely randomized design using analysis of variance (ANOVA). Each treatment was performed in three replicates, and mean comparisons were conducted using Duncan's test at a 95% significance level.

RESULTS AND DISCUSSION

Figure 1 displays the FTIR spectra of oxidized and non-oxidized fibers at different treatment levels. The peak near 1650 cm^{-1} represents carboxyl groups, formed during the oxidation of cellulose by oxidizing agents (Coseri *et al.* 2009). It should be noted that minor baseline drifts and differences in intensity among the FTIR spectra were observed. These variations can arise from differences in fiber thickness, moisture content, or sample compaction during pellet preparation. Therefore, the analysis focused mainly on the relative positions and presence of characteristic absorption peaks (particularly near 1650 cm^{-1}) rather than on absolute peak heights or areas. Despite the intensity variations, the presence and shift of the characteristic C=O stretching band clearly indicate the formation of carboxyl groups on the oxidized fibers. This figure highlights the changes in carboxyl group content before and after oxidation using varying concentrations of H_2O_2 .

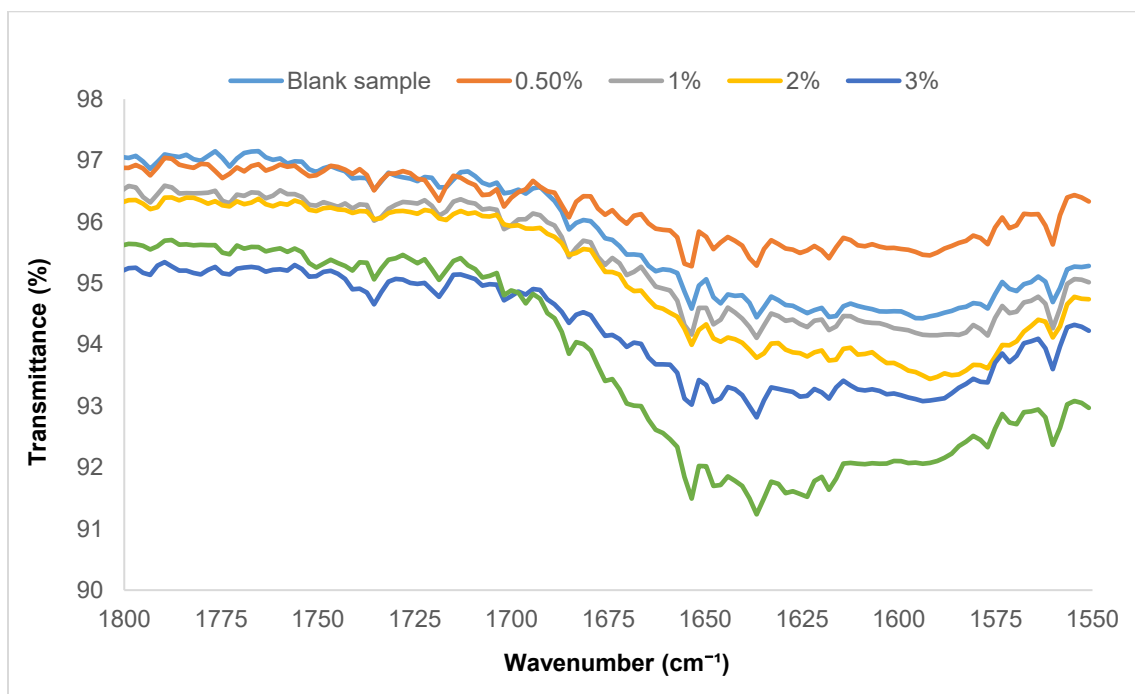


Fig. 1. Spectroscopy of the modified OCC fibers by different levels of H_2O_2

Figure 2 shows the quantified carboxyl group content in treated and control samples. The results indicate that the highest carboxyl group content corresponded to the treatment with 1% H_2O_2 , while the control sample exhibited the lowest content. Bhardwa and Nguyen (2005) observed in their study that increasing the concentration of H_2O_2 did not significantly affect carboxyl group formation. This finding aligns with the results of the present research (Carlsson *et al.* 2005). Oxidation of cellulose fibers introduces carboxyl groups at the C6 position, altering the structure and properties of the fibers. Several oxidation methods, including non-persistent nitroxyl radicals (Biliuta *et al.* 2010), $\text{HNO}_3/\text{H}_3\text{PO}_4\text{-NaNO}_2$ mixtures (Xu *et al.* 2014), H_2O_2 (Nogués *et al.* 2002), and N-hydroxyphthalimide with co-catalysts (Coseri *et al.* 2009), have been explored. These treatments enhance carboxyl content, reduce crystallinity, and affect thermal stability (Xu *et al.* 2014). Furthermore, the hydrophilic carboxylate groups formed during oxidation have been reported to improve water resistance by 30% to 35% compared to untreated fibers (Coseri *et al.* 2009; Biliuta *et al.* 2010).

Amount of Carboxyl Groups

As illustrated in Fig. 2, increasing the concentration of H_2O_2 led to a decrease in the amount of carboxyl groups. A comparison between Figs. 1 and 2 confirms the variations in carboxyl group content between treated and control samples.

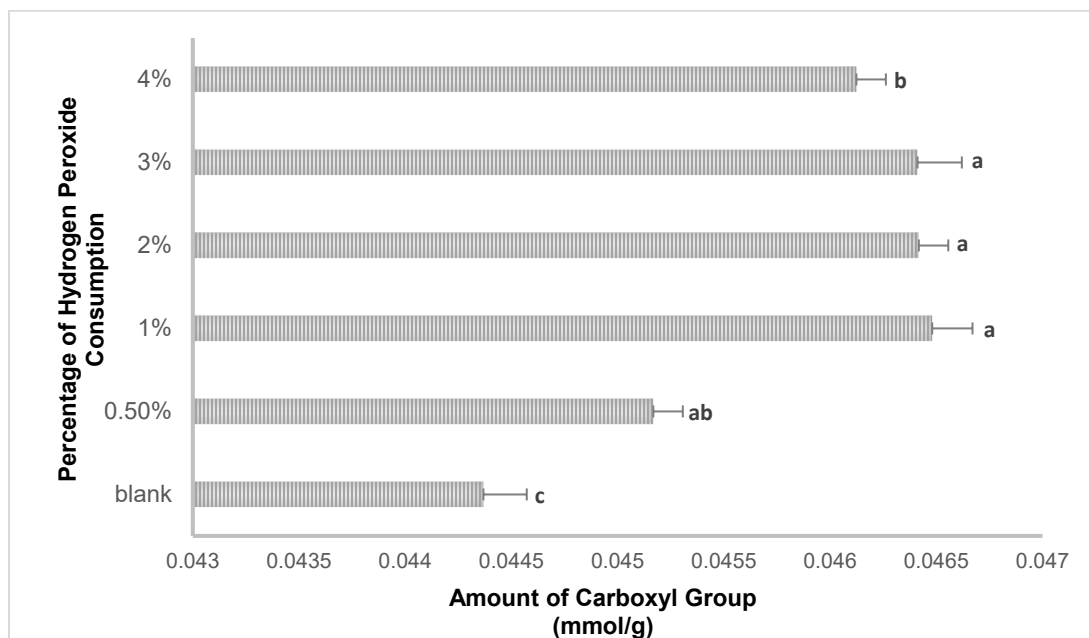


Fig. 2. Amount of the carboxyl groups of the OCC pulp at different H_2O_2 levels. Different letters indicate statistically significant differences ($p < 0.05$) according to Duncan's multiple range test.

Carboxyl groups, which are ionizable functional groups, are naturally present in wood fibers. During alkaline decomposition, carboxylic acid groups form at the reducing ends of cellulose and hemicellulose chains. These groups can also be generated through oxidative treatments, such as decolorization using H_2O_2 . Hemicelluloses naturally contain these carboxyl groups (Bhardwaj and Nguyen 2005). During the oxidation process, hydroxyl groups in glucosides and cellulose monomers are oxidized to aldehyde or carboxyl groups. Thus, oxidation with H_2O_2 is an effective method for increasing the carboxyl group content in fibers. Li *et al.* (2020) reported that in the oxidation of paper

pulp with H_2O_2 , the carboxyl group content initially increases but declines as the concentration of H_2O_2 continues to rise. Their research showed that the maximum carboxyl group content, recorded after oxidation, was $165 \mu\text{mol/g}$, compared to $107 \mu\text{mol/g}$ in non-oxidized pulp. These findings are consistent with the results obtained in this study, further confirming the trend observed in the oxidation process (Li *et al.* 2020). At higher hydrogen peroxide concentrations (*e.g.*, 4%), a slight decrease in the measured carboxyl content was observed. This trend can be attributed to over-oxidation and partial solubilization of hemicellulosic components and low-molecular-weight oxidation byproducts into the solution phase. Excessive peroxide levels may also promote fiber degradation and the breakdown of amorphous cellulose regions, resulting in the removal of oxidized fragments during washing. Such over-oxidation behavior has been reported in previous studies on peroxide-treated pulps (Li *et al.* 2020; Martinsson *et al.* 2022). The observed results therefore reflect the balance between oxidation-induced carboxyl formation and subsequent loss of oxidized polysaccharide fragments at higher H_2O_2 concentrations.

Scanning Electron Microscopy

Figure 3 shows images obtained by scanning electron microscopy (SEM). Figure 3a depicts the control sample, while Fig. 3b presents non-oxidized fibers treated with PVOH. Figure 3c illustrates hydrogen peroxide-modified fibers, and Figure 3d shows fibers that had been both modified and treated with PVOH.

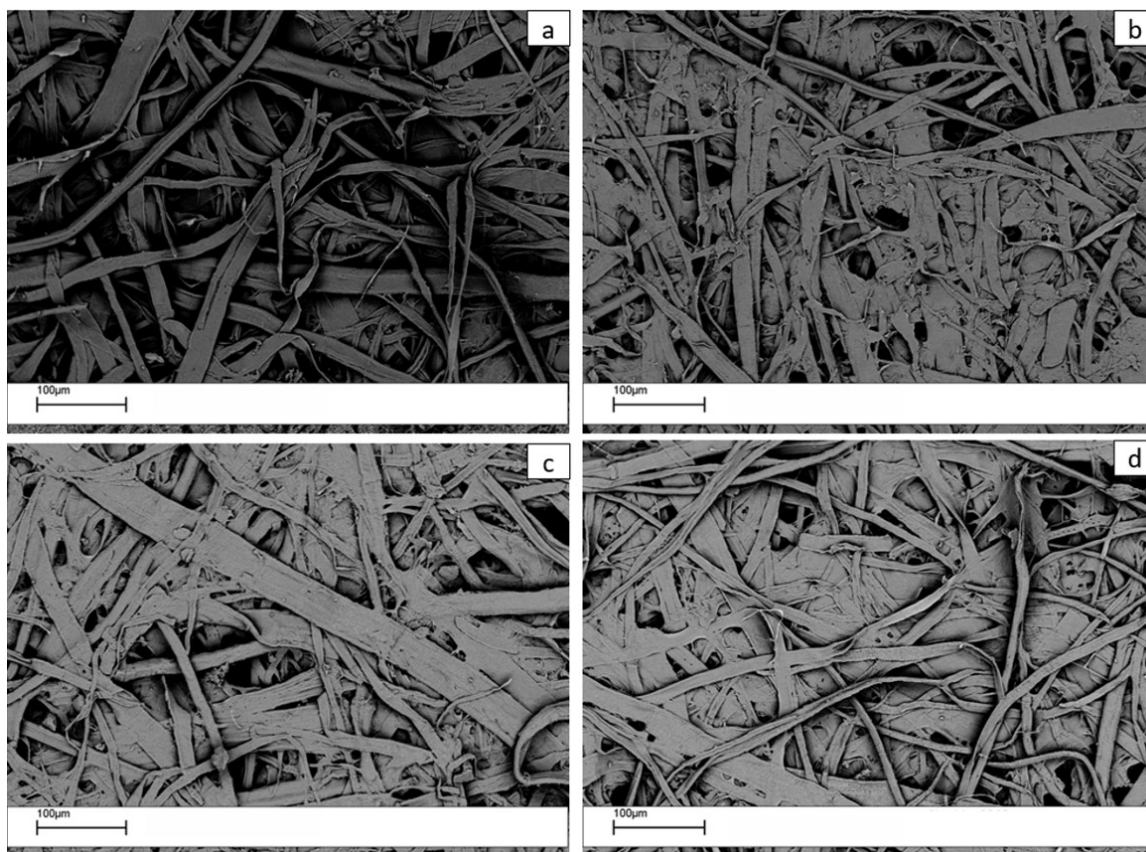


Fig. 3. Images obtained by scanning electron microscopy (SEM). Figure 3a depicts the control sample, while Fig. 3b presents non-oxidized fibers treated with PVOH. Figure 3c illustrated hydrogen peroxide-modified fibers, and Figure 3d showed fibers that have been both modified and treated with PVOH.

The SEM images revealed that paper samples oxidized with H_2O_2 exhibited less porosity than those produced without oxidative surface modification. These results emphasize the role of H_2O_2 in forming new chemical bonds and functional groups on the fiber surface, which enhances the adhesion of PVOH to the fibers. In other words, surface modification increases the number of functional groups on the cellulose fibers, which can interact with PVOH, promoting better retention of PVOH on the surface. This process also helps to fill the spaces between fibers and may eventually increase the smoothness of the paper surface. Conversely, paper samples produced without oxidative surface modification exhibited greater porosity due to insufficient bonding with the fibers and poor distribution of PVOH. In these samples, PVOH did not adhere uniformly to the fibers, creating voids and holes in the paper structure, which ultimately reduced the quality and mechanical strength of the paper.

Mechanical Properties of the Paper

Figure 4 showed the tensile strength of oxidized and non-oxidized OCC fibers with and without PVOH. There was also a blank sample, which contained non-oxidized OCC fibers without PVOH.

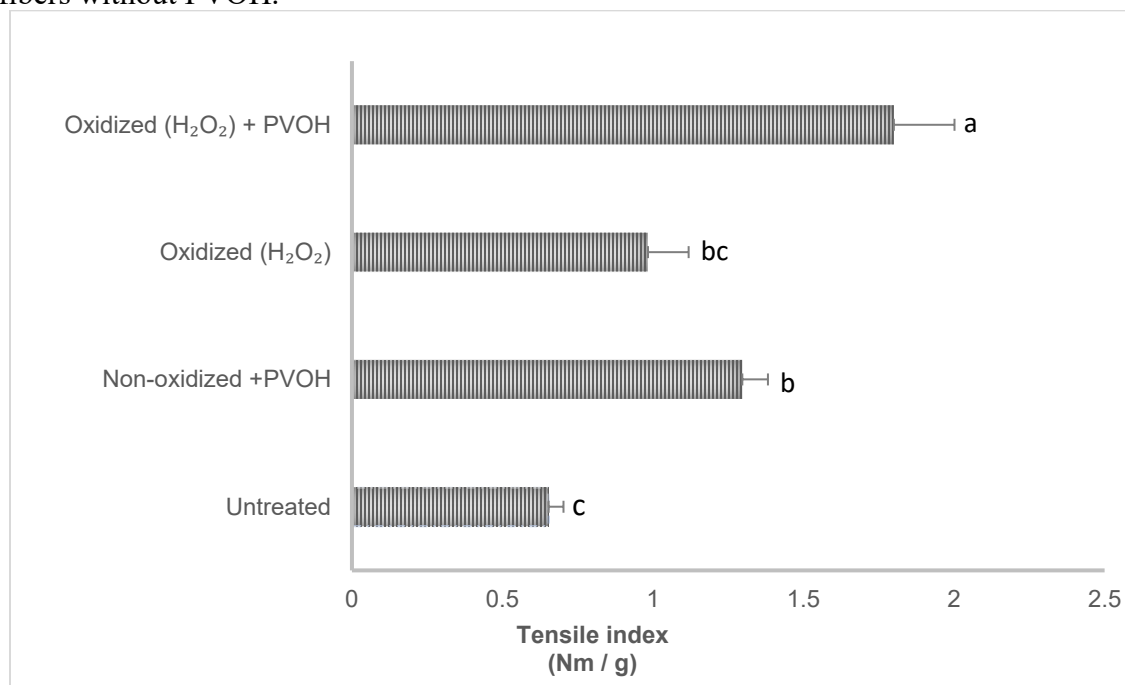


Fig. 4. The effect of PVOH on the tensile index of the papers. Different letters indicate statistically significant differences ($p < 0.05$) according to Duncan's multiple range test.

As shown in the Fig. 4, the use of PVOH increased the tensile strength of OCC recycled papers. However, the modification of the fiber's surface by H_2O_2 increased the efficiency of PVOH and increased the tensile strength of the paper compared to the non-oxidized sample. The variance analysis of the tensile strength of the samples showed that the difference between the means was significant at the 5% confidence level. Modifying the fiber surfaces with H_2O_2 can increase the carboxyl functional group, and the carboxyl groups on the pulp fiber surfaces can significantly increase the ionic bonds between the fibers, provided that the fiber surfaces have large amounts of carboxyl groups. Gupta *et al.*

(2021) in their study showed that H_2O_2 can improve the tensile strength of the fibers. Certainly, increasing the concentration of carboxyl groups in paper had a significant effect on its tensile strength (Gupta *et al.* 2021). Carboxyl groups are functional groups when incorporated into the paper matrix, they create additional sites for interaction between fibers. The presence of carboxyl groups increases hydrogen bonding and the possibility of forming ester bonds between cellulose fibers (Wen *et al.* 2019). Improving, and increasing the bond between fibers significantly contributes to the tensile strength of paper and makes paper more resistant to tensile forces. As a linear polymer, PVOH, which has many hydroxyl groups on its surface, can interact and bond with functional groups on the surface of paper's fiber. These links may increase fiber density and reduce porosity in the paper structure, as was observed in examining the morphological structure of treated paper fibers by SEM. These changes can lead to an increase in the tensile strength of the paper. In other studies, it was observed that PVOH increases the number of hydrogen bonds between cellulose fibers, which leads to higher tensile strength these connections increase the durability and mechanical integrity of paper (Tarnowiecka-Kuca *et al.* 2023). As can be seen in Fig. 4, the oxidized paper with PVOH had highest strength compared to non-oxidized samples. Therefore, it can be concluded that oxidation of surface improved the efficiency of PVOH in papers. Figure 5 showed the burst index of oxidized and non-oxidized OCC fibers with PVOH.

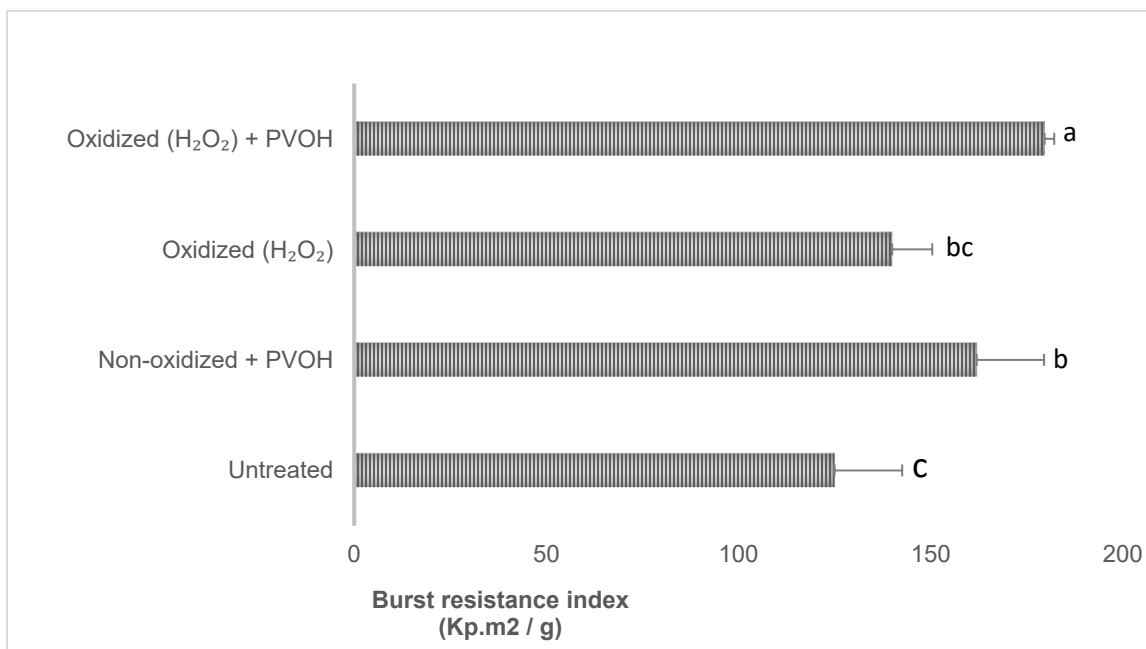


Fig. 5. The effect of PVOH on the burst index of papers. Different letters indicate statistically significant differences ($p < 0.05$) according to Duncan's multiple range test.

The highest burst index is related to the samples of oxidized fibers and PVOH. The addition of PVOH to unmodified surface of the fibers also caused a relative increase in burst index. The lowest strength was found for the control sample. In general, the characteristics of burst index and stretching are closely related to each other, and with both tests, the effect of the degree of connection of fibers with each other and the density of the fiber's network could be well observed. Increasing the number of hydrogen bonds increases the bonding strength between fibers, and this increase in bonding prevents the fibers from slipping and increases the strength of the fiber's network. The oxidation of the surface of

the fibers is a technique to change the type and number of bonds between fibers used in paper production to modify the surface and strength properties of the paper. Burst index is especially important for applications where the paper is exposed to mechanical stresses or high-pressure environments (such as packaging materials). Oxidation of the fiber's surface can lead to the increase of hydrogen bonds between fibers. This increased adhesion can increase the internal strength of the paper and make it more resistant to bursting. Improved inter-fiber bonding leads to better stress distribution in the paper matrix. Also, oxidized fibers have changed surface charges and higher surface energy. This can lead to better distribution of chemicals and additives during the papermaking process. In addition to increasing the reactivity of the fibers, this can lead to the uniformity of the resistances on the surface of the paper. Therefore, the increased interaction between fibers and additives can lead to improved fiber dispersion, which creates paper with more uniform structure and ultimately better resistance to bursting. Incorporating PVOH into the papermaking process can have a significant impact on burst index, often resulting in improvements in strength due to its unique properties and effects on paper structure. The use of H_2O_2 in an alkaline environment has led to the oxidation of cellulose fibers and increase of carboxyl groups on the fiber's surface. These changes are caused by cellulose oxidation reactions that convert hydroxyl groups in different places of the cellulose chain (mainly at C2 and C3) into carboxyl or ketone groups. Scientific studies show that H_2O_2 in alkaline conditions produces hydroxyl radicals that play an important role in this oxidation and can ultimately help improve fiber properties such as wet or dry strength (Vera-Loor *et al.* 2023; Koschevic *et al.* 2024). Figure 6 shows the tear index of the oxidized and non-oxidized OCC fibers with and without PVOH. The results showed that the use of PVOH in OCC recycled papers increases the tear index of the papers and is statistically significant at the 5% confidence level.

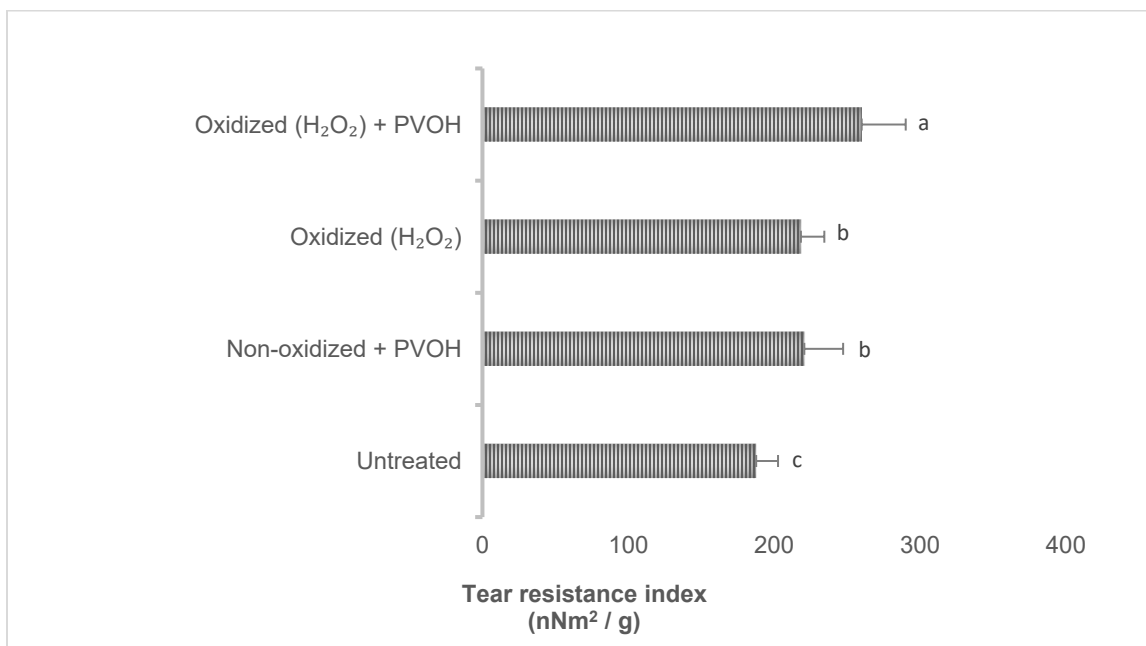


Fig. 6. The effect of PVOH on the tear index of papers. The effect of PVOH on the burst index of papers. Different letters indicate statistically significant differences ($p < 0.05$) according to Duncan's multiple range test.

The priority of factors influencing the tear index primarily depends on the fiber length and the inherent strength of the fibers. However, when these two factors are constant, the bonding between fibers plays a significant role in determining the paper's resistance to tearing. The presence of carboxyl groups on the fiber surface increases bonding between fibers. These groups not only enhance hydrogen bonds but also facilitate the formation of covalent bonds, thereby improving the mechanical strength of the paper against tearing. Gupta *et al.* (2021) reported that H_2O_2 improves the inherent strength of fibers. Additionally, they showed that using H_2O_2 under alkaline conditions increased the carboxyl group content, removes lignin, enhances fiber purity, and positively affects the strength properties of the fibers (Gupta *et al.* 2021; Axel 2022).

Water Absorption

The average values of water absorption of different treatments were significant at the 95% confidence level. Also, based on Duncan's test, the average values of water absorption have been placed in 2 groups. Next, the effect of different treatments on the water absorption of treated and control papers is shown in Fig. 7.

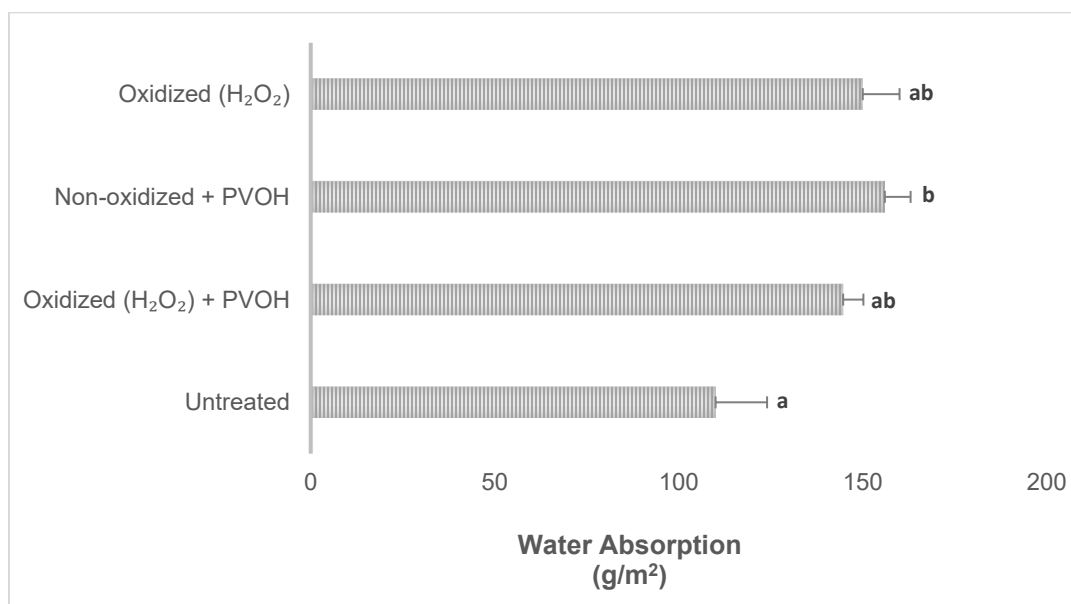


Fig. 7. The effect of PVOH on the water absorption of papers. The effect of PVOH on the burst index of papers. Different letters indicate statistically significant differences ($p < 0.05$) according to Duncan's multiple range test.

As can be seen, the water absorption of the papers increased with treatments, so the control sample had the lowest amount of water absorption. The water absorption test is an important method in evaluating the quality of paper to determine the ability of paper to absorb and retain water. This test is used in various industries such as printing and packaging, cardboard production, *etc.* Water absorption of the papers increased after oxidation by H_2O_2 . This result showed the chemical modification of the fibers' surface. The H_2O_2 , especially in an alkaline environment, produces reactive oxygen species such as hydroxyl radicals. These radicals oxidize cellulose fibers decompose components such as lignin and introduce hydrophilic functional groups such as hydroxyl (OH) and carboxyl (COOH) groups on cellulose chains. These groups are polar and attract water molecules through hydrogen bonding, thereby increasing the water absorption capacity of the paper.

This phenomenon is supported by studies that highlight the relationship between the increase in surface hydrophilicity and the increase in water absorption after oxidation treatment by increasing the number of hydrophilic functional groups. The oxidation process also may partially disrupt the crystalline structure of cellulose.

Cellulose is comprised of a combination of crystalline and amorphous regions. The amorphous regions are more flexible and susceptible to swelling in water. Oxidative treatments often increase the proportion of amorphous cellulose regions and increase the fiber's ability to absorb water. In general, studies have shown that oxidized cellulose fibers directly contribute to the absorption of more water by the structural changes mentioned. Also, PVOH increases the water absorption of paper, which can be attributed to the hydrophilic nature of PVOH. The PVOH contains numerous hydroxyl (OH) groups along its polymer backbone that interact with water molecules through hydrogen bonding. When PVOH is added to cellulose fibers, it increases the hydrophilicity of the paper matrix, allowing it to retain more water. In addition, PVOH can form a continuous layer on the surface of fibers that creates microenvironments that trap water molecules and increase overall water retention. Scientific studies support these findings and show that the hydrophilic properties of PVOH can significantly increase the water absorption capacity of cellulose-based composites. In addition, PVOH improves the bonding between individual cellulose fibers, resulting in a more cohesive and uniform paper structure. This reinforced fiber bonding, combined with PVOH's hydrophilicity, results in an overall increase in water absorption. The interaction between PVOH and cellulose, as well as improved fiber bonding, has been documented in studies focusing on the mechanical properties and water absorption of PVOH cellulose composites. These studies confirm that the addition of PVOH not only improves fiber bonding but also increases the paper's ability to absorb water.

Oil Resistance

The oil resistance of the treated papers based on the amount of oil passing through the samples and the area of the drying paper that is soaked in oil showed in Fig. 8.

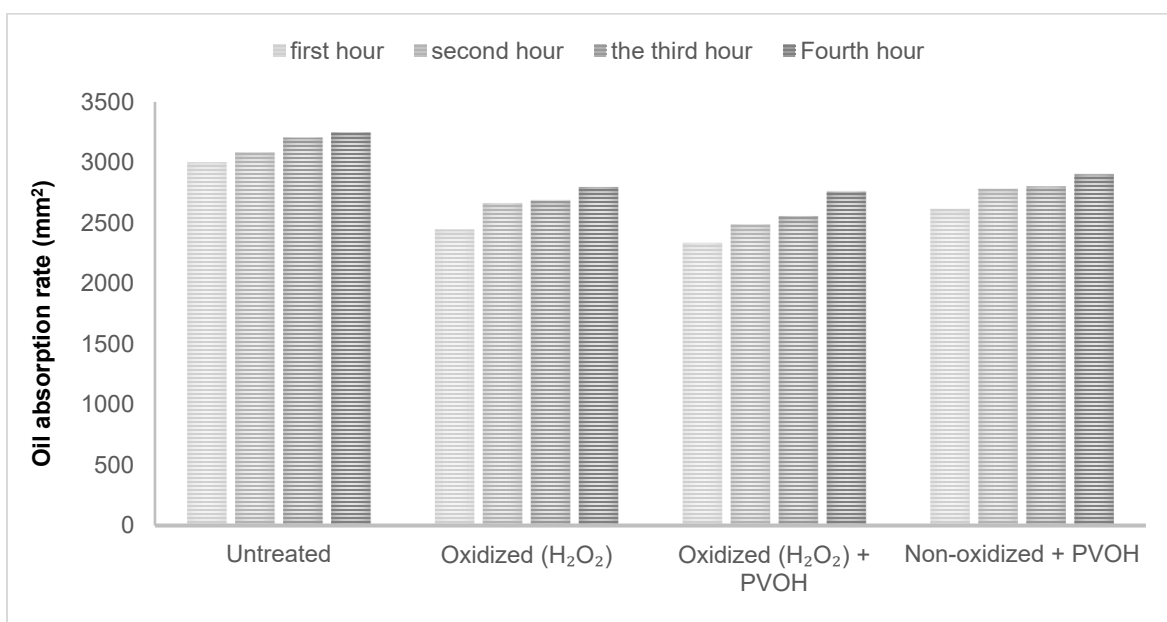


Fig. 8. The effect of PVOH on the resistance to fat penetration of papers

In this test, the smaller the area covered with oil, the greater the paper's resistance to oil absorption. As can be seen in Fig. 8, the treatments reduced the amount of oil passage in the papers. The control sample had the most oil passage in four hours. Checking the absorption of oil can help to evaluate the resistance of paper against the penetration of oily substances. This feature can be very important in all types of paper that come into contact with oily liquids, such as food packaging, cosmetic products, *etc.* Oxidation of fibers by using H_2O_2 , as an oxidizing agent can lead to an increase in the oil resistance of the paper because oxidation affects the structure and physicochemical properties by increasing the polarity. The surface of the paper leads to the resistance of the paper's surface to non-polar factors. These changes can lead to the creation of hydrophilic coatings on the fiber's surfaces, which effectively prevent the penetration of oil and increase the oil resistance of the papers. Oxidation can cause changes in the internal molecular structure of the fibers. These changes may increase the bonding between fibers and can lead to reduction in the porosity of the paper structure. This can limit oil passage and help increase oil penetration resistance, thus increasing oil penetration resistance. The effects of PVOH on the passage of oily substances in paper and other materials can be diverse. Due to its hydrophilic nature, PVOH can reduce the hydrophobic properties of the surface of paper or different materials used in it. This can lead to an increase in density and non-absorption of oily substances in the structure of the material and an improvement in the resistance to their passage (Shen *et al.* 2019). Also, PVOH may be formed in the form of layers on the surface of the material, which increases the density of the material and consequently restricts the passage of substances such as oil. Increasing the density and creating a denser structure in the material causes the passageways of oily substances to become more limited and the resistance to their passage increases. In general, the effects of PVOH on the passage of oily substances can be related to the surface and internal density, hydrogen interactions, and the hydrophobic or hydrophilic properties of the substances. These properties may be used in various applications such as packaging and oil-resistant papers (Huang *et al.* 2022).

CONCLUSION

This study investigated the effects of oxidizing cellulose fibers using H_2O_2 and the addition of poly(vinyl alcohol) (PVOH) on the mechanical, structural, and chemical properties of recycled paper.

1. The results demonstrated that the oxidation process increased the carboxyl group content on the fiber surfaces, significantly enhancing inter-fiber interactions and improving their bonding strength. The presence of carboxyl groups increased the bonding capacity between fibers, which contributed to the improved tensile strength, burst index, and tear index of the paper.
2. Scanning electron microscopy (SEM) revealed that the treatment reduced porosity and promoted better adhesion of PVOH to the fiber surfaces, resulting in a smoother and more uniform paper structure.
3. Additionally, PVOH contributed to the mechanical strength by forming hydrogen bonds with cellulose fibers, increasing fiber density and minimizing structural porosity. The introduction of hydrophilic functional groups, such as carboxyl and hydroxyl groups, improved water absorption capacity. Furthermore, the enhanced surface polarity and reduced porosity resulting from the treatment increased resistance to oil

penetration, making the paper suitable for applications requiring oil-resistant properties, such as packaging materials.

4. The combined oxidation with H₂O₂ and incorporation of PVOH resulted in marked improvements in both mechanical and functional properties of the paper. However, the enhancement pattern suggests that the effects were primarily additive rather than strongly synergistic, as each treatment contributed independently to the overall improvement oxidation by increasing surface reactivity and PVOH by reinforcing inter-fiber adhesion. Despite this, the combined process demonstrated a high level of effectiveness, producing a cost-efficient and environmentally friendly method for improving OCC fiber-based materials under mild conditions.
5. Overall, the developed approach offers a practical and scalable strategy for the production of advanced cellulose-based materials with enhanced performance characteristics suitable for industrial packaging applications.

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Conflicts of Interest

The authors declare no conflicts of interest.

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