Turkish Journal of Forest Science
Available online at dergipark.gov.tr/turkjforsci

COMPARATIVE EVALUATION OF OIL BARRIER AND STRENGTH PERFORMANCE OF POLYMER-COATED PAPERS FROM RECYCLED WASTEPAPER FOR FOOD PACKAGING

Tamer SÖZBİR[1]

[1]Department of R&D, KİPAŞ Kağıt Sanayi İşletmeleri A.Ş:, Kahramanmaraş

*Corresponding author: tamersozbir@hotmail.com

Tamer SÖZBİR: https://orcid.org/0000-0001-9035-8214

Please cite this article as: Sözbir, T. (2025) Comparative evaluation of oil barrier and strength performance of polymer-coated papers from recycled wastepaper for food packaging. *Turkish Journal of Forest Science*, 9(2), 296-312.

ESER BİLGİSİ / ARTICLE INFO
Araştırma Makalesi / Research Article
Geliş 17 Haziran 2025 / Received 17 June 2025
Düzeltmelerin gelişi 28 Temmuz 2025 / Received in revised form 28 July 2025
Kabul 1 Ağustos 2025 / Accepted 1 August 2025
Yayımlanma 27 Ekim 2025 / Published online 27 Ekim 2025

ABSTRACT: This study investigates packaging papers produced from recycled wastepaper in terms of oil resistance and mechanical performance, especially for fast food applications. Five different polymers known for their compatibility with paper substrates and oil barrier properties were applied to the paper surface using a laboratory-scale size press. Oil resistance was evaluated using the TAPPI T559 kit test method, and mechanical strength was measured through standard tensile strength and SCT (short-span compression test) methods. Polymers D and E exhibited excellent oil barrier properties, with minimal permeation (4 mm) after 12 hours, while also maintaining strong SCT performance (up to 2.275 kN/m). In contrast, although polymers A and B were less effective in oil resistance, polymer A demonstrated outstanding tensile strength (2355 Nm/kg), making it a suitable option for applications requiring high mechanical strength. The findings suggest that polymers D and E are ideal for long-term barrier applications, whereas polymer A is more suitable where mechanical durability is prioritized. The study emphasizes the need for further research on polymer formulations, particularly bio-based and eco-friendly alternatives, to support the development of sustainable and high-performance paper-based packaging materials.

Keywords: Polymer coatings, oil-resistant papers, recyclable materials, cellulose-based materials

GIDA AMBALAJI İÇİN GERİ DÖNÜŞTÜRÜLMÜŞ ATIK KAĞITTAN ÜRETİLEN POLİMER KAPLI KAĞITLARIN YAĞ BARİYERi VE MEKANiK PERFORMANSLARININ KARŞILAŞTIRMALI DEĞERLENDİRMESİ

ÖZET: Bu çalışma, geri dönüştürülmüş atık kağıttan üretilen ambalaj kağıtlarının özellikle fast food ambalajlarında kullanımına yönelik olarak yağ direnci ve mekanik performans açısından değerlendirilmesini amaçlamaktadır. Kağıt yapısı ile uyumlu ve yağ bariyer özellikleri ile bilinen beş farklı polimer, laboratuvar tipi bir yüzey kaplama cihazı (size press) ile kağıt yüzeyine uygulanmıştır. Yağ direnci TAPPI T559 kit testi yöntemi ile, mekanik dayanım ise standart çekme dayanımı ve kısa span sıkıştırma testi (SCT) ile ölçülmüştür. Polimer D ve E grupları, 12 saat sonunda yalnızca 4 mm'lik geçirim ile mükemmel yağ bariyeri özellikleri göstermiş ve aynı zamanda yüksek SCT performansı (2.275 kN/m'ye kadar) korumuştur. Buna karşın, polimer A ve B yağ direnci açısından daha düşük performans sergilemiş olsa da, polimer A olağanüstü çekme dayanımı (2355 Nm/kg) ile dikkat çekmiş ve yüksek mekanik dayanım gerektiren uygulamalar için uygun bir seçenek olduğunu göstermiştir. Elde edilen bulgular, polimer D ve E'nin uzun süreli bariyer uygulamaları için ideal olduğunu, polimer A'nın ise mekanik dayanımın ön planda olduğu uygulamalar için daha uygun olduğunu ortaya koymaktadır. Çalışma, sürdürülebilir ve yüksek performanslı kağıt ambalaj malzemelerinin geliştirilmesine katkı sağlayacak biyobazlı ve çevre dostu polimer formülasyonlarına yönelik daha ileri araştırmalara duyulan ihtiyacı vurgulamaktadır.

Anahtar kelimeler: Polimer kaplamalar, yağ geçirmez kağıtlar, yeri dönüştürülebilir malzemeler, selüloz bazlı malzemeler

INTRODUCTION

The application of oil-repellent chemicals to the surface and structure of cellulose-based materials represents an important approach for developing environmentally friendly, cost-effective, and innovative products. Papers produced using this method have significant potential, particularly in the rapidly growing fast-food packaging sector, and various other industries. By providing an alternative to petroleum-based packaging materials, increasing paper-based product use contributes not only to reducing imports and encouraging local production but also to ensuring environmental sustainability.

Achieving water and oil repellency on paper surfaces is a prominent research area, especially for food packaging applications. Sharif et al. (2023) highlighted the extensive use of both oligomeric (e.g., phosphates, carboxylates, quaternary ammonium salts) and polymeric (mainly copolyacrylates) fluorochemicals to impart water, oil repellency, and stain release on surfaces such as paper, textiles, and stone. Papers treated with these additives were shown to enhance grease and oil resistance, ensuring the necessary durability for food packaging. The study also emphasized that oil repellency can be evaluated through the simplest method of measuring the paper's resistance to hydrocarbon droplet surface tension. Since water can cause excessive swelling in cellulosic material and negatively affect oil repellency, achieving water repellency is equally critical (Sharif et al. 2023).

Basak et al. (2024) emphasized the use of water- and oil-repellent paper sheets, particularly for oily food packaging, stressing the importance of balancing safety and performance rather than achieving complete water and oil impermeability. Similarly, Billmers (2004) proposed the use of starch and high-strength, water-soluble protein in paper-sizing compositions, improving oil and grease resistances under various atmospheric conditions. They demonstrated that low-amylose starch effectively enhances oil resistance. Yamaguchi and Yaguchi (1996) found that monomers containing C4–C16 polyfluoroalkyl groups are effective agents for improving water and oil resistances, offering high performance even at low viscosities. They also noted that these copolymer-based agents achieve greater water and oil resistances when combined with cationic strengthening agents. Wei et al. (2018) reported that short-chain polyfluoroalkyl-containing copolymers deliver superior oil and water resistances, highlighting their promising applications in the packaging industry.

Specifically, this study incorporates fluorocarbons with different chain lengths (Florakarbon 6 and Florakarbon 8), a dendrimer “Polyamidoamine” (PAMAM), and a fluoropolymer. The pH values of these polymers vary between 2.0 and 5.5, while their densities range from 1.03 to 1.1 g/cm^3. These variations in chemical composition and physicochemical properties are expected to influence the performance characteristics observed in the experimental results. Fluorocarbons [especially short-chain (C6) and long-chain (C8) types] have been employed extensively for preparing water/oil repellent coatings on cellulose-bearing surfaces. The chemical characteristics and environmental aspects of these polymers—including toxicity, chain length, and functional groups—are briefly discussed in the introduction and supported by relevant literature (e.g., Cui et al. 2011; Jung et al. 2022).

Dendrimers represent a polymeric nanostructure with high degrees of branching ideal for oil-impermeable back sheets within the paper industry. Their branched architecture provides them with suitable coating as it allows even coating and oleophobic properties which improve the performance in oil and grease resistances of paper. Polyamidoamine (PAMAM) based dendrimers in their modified form, for example fluorine-functionalized polyamidoamine (Cui et al. 2011) can be utilized to form hydrophobic layers on the paper surface, thus opening a viable avenue towards applications such as food packaging. They could also be used for surface energy control and sustainable production processes (Ladd 2012). Fluoropolymers are being widely used in the paper industry as excellent oil- and water-repellent coatings which deliver an innovative solution in order to enhance paper performance/durability (particularly for packaging applications). These are inherently resistant to oils and greases, quite useful within food packaging where oil contamination is a hindrance.

In the paper sector incorporation of fluoropolymers as barrier can help us to reduce overreliance on conventional plastic-based packaging and it provide a more sustainable alternatives. Not only will this improve the paper products but help support eco-friendly efforts, as it increases recyclability and results in a lesser environmental effect (Glenn et al. 2021; Hossain et al. 2022). However, the persistence and toxicity of fluorocarbons even with low carbon chain lengths of 6 or less is a major concern (Wang et al. 2013; Schaider et al. 2017). Undoubtedly the take away from this should be the recognized (known and alternative) solutions existing today.

Tayeb et al. (2020) reported a new lignin-containing cellulose nanofibrils (CNFs) for oil-barrier packaging. Their contributions highlighted CNFs capability to improve water and oil repellence in paper. The methods of preparation were outlined, together with the finding that carboxylate nanocellulose addition led to very strong improvements in barrier properties of paper as it was still applicable for applications requiring both water and oil resistant. Wang et al. (2024) in a follow-up study, ecologically designed oil- and water-resisting papers with holo-lignocellulosic nanofibrils (LCNF). The combination of LCNF and gelatinized starch in a composite coating resulted in not only exhibit superior mechanical strength but greatly enhanced super hydrophobicity of paper. Experimental contact angle for oil and water quantitatively confirmed the efficiency of LCNF-based coating. They also talked about the potential of converting agricultural residues like wheat straw to produce LCNF to achieve a greener solution in paper manufacture (Wang et al. 2024).

In summary, based on reported studies, there is a need to develop chemical treatments and processes to improve oil/water resistances in papers based on cellulose. More advanced bio-based polymers and nanofibril coatings will open the way for the sustainable production of premium materials for food packaging.

MATERIALS and METHODS

In this study, five different polymers—including dendrimers, fluorocarbons, and fluoropolymers—were applied to recycled paper substrates to evaluate their effects on oil resistance and mechanical properties. All polymer samples were applied using a laboratory-scale size press, and tests were conducted following TAPPI standard methods.

This is also done with the paper sample used in experiments, 150 g/m² of fluting paper produced from recycled paper of Kahramanmaraş Paper Factory. Others, oil kit for resistance tests have been prepared. These kits were designed to model the many group oil families usable in industry so as to permit and potential application areas for oil-resistant papers.

The oil-repellent chemicals were applied to the paper samples using a laboratory scale size press. It accurate device was developed for evenly transferring chemicals onto paper surface being exposed homogenously. After exposure, the treated samples were conditioned for testing after treatment. All chemicals used in the study were certifid as safe for direct contact with food products. The mechanical properties were evaluated using standardized methods. The tensile strength was determined according to TAPPI T494, burst strength by TAPPI T403, and short-span compression test (SCT) by TAPPI T826. The oil resistance was evaluated through the TAPPI T559 kit test, and water absorptiveness (Cobb value) was calculated according to TAPPI T441.

The aim of this study is to describe the method used for the evaluation of the Kıt grease resistance of papers. This method describes a procedure to characterize the resistance of papers to grease. The Kit test method involves applying test solutions numbered from 1 to 6, to the sample under evaluation. The test is carried out under the guidelines of Tappi test method for grease resistance for paper and paperboard T 559 (TAPPI, 2022). Kit test solutions composed of Castor oil, Toluene, and Heptane. A drop is applied to the test papers using a dropper. The timer is started. The spread of the droplet is observed and monitored. Calculated the sizing degree (or cobb value) in g/m², using Eq. 1 (TAPPI, 2021).

$$\text{Cobb 60 s (g/m2)} = (W_{wet} - W_{dry}) * 100 \tag{1}$$

Where Wwet denotes weight of the base paper after the test, and Wdry is the weight of the dry base paper measured in grams.

Table 1 presents the polymers utilized in this study, along with their chemical codes, pH ranges, and densities. The selected polymers include fluorocarbon-based compounds and dendrimers, which are known for their distinct chemical properties and potential applications in surface modifications.

Table 1. Polymers Used

Chemical Code	Chemical Structure	pH	Density (g/cm³)
A	Fluorocarbon+Dendrimer	2-5	1.03
B	Dendrimer (PAMAM)	3.5-5.5	1.1
C	Fluorocarbon C6	2-5.5	1.07
D	Fluorocarbon C8	4-4.5	1.07
E	Fluoropolymer	2.1-2.5	1.05

The most accepted way to evaluate greaseproof papers that have been treated in some way with perfluorinated compounds is called the kit test, which is specified in TAPPI Method T559 cm-02 (TAPPI 2022). This test uses a series of 12 solutions with different ratios of castor oil to toluene to n-heptane. The aggressiveness of the test solutions increases with increasing content of heptane and decreasing content of castor oil. In this study, as seen in Table 2, the 6-kit method will be used.

Table 2. The Mixture Ratios of the Oil Kits Used in the Oil Resistance Tests

Oil Test Kit No	**Castor Oil (mL)**	**Toluene (mL)**	**n-Heptane(mL)**
1	100	0	0
2	90	5	5
3	80	10	10
4	70	15	15
5	60	20	20
6	50	25	25

As can be seen from Figure 1, the tester uses an eyedropper to drop a selected solution of intermediate “kit number”, around 13 mm onto the surface of subject paper on a flat dark background which usually rests on top of a clean surface while being pipetted. The droplet is wiped after 15 s, and if the underlying area does not darken, the effect of filling voids on the paper with the test fluid is considered “failure” of the test. Until then tester repeats until he identifies the max kit number with a that he would call “pass” (Figure 1-a;) Hubbe and Pruszynski 2020).

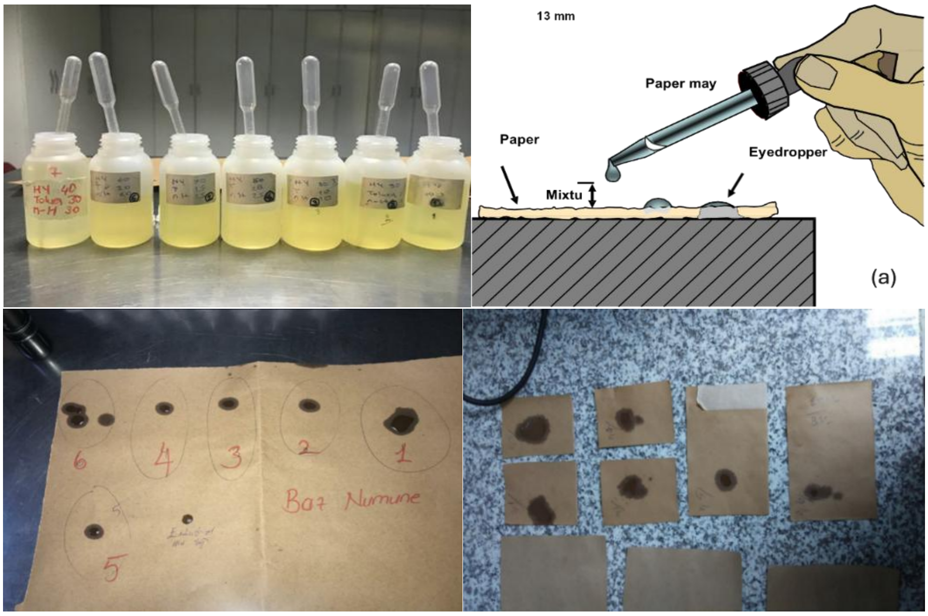

Figure 1. Schematic Illustration of the “Kit Test” (TAPPI Method T559) for Determination of the Extent

A starch solution (500 mL) with 4% dry matter concentration was prepared at 90 °C. Approximately 3 g of polymer was added to the supernatant and mixed thoroughly on a heated magnetic stirrer for 10 minutes to obtain a uniform solution. The homogeneous polymer-starch mixture was then applied to both sides of the laboratory-prepared paper samples using a size press apparatus in Figure 2.

Figure 2. Laboratory-type Surface Application Sizing Press Unit.

Following the application, the samples were dried using the drying section of a Rapid-Köthen sheet former at 101 ± 3 °C for several minutes without load. Afterwards, the samples were conditioned under standard atmosphere. All treatments and tests were carried out in five replicates. Oil resistance tests were conducted on the functional (top) surface of the coated papers. These procedures allow for effective integration of polymer-infiltrated coatings onto paper substrates and provide consistent conditions for subsequent analyses. Kjellgren and Engström (2005) reported that the required amount of refining could be decreased by application of hydrophilic polymers at the size press, followed by calendering.

RESULTS AND DISCUSSION

Surface Application

Oil resistance in experimental papers

Since the fluorochemical treatment of paper is intended to modify the paper's outer surface, it is logical to apply the treatment using a size press or other equipment that facilitates surface application (Szymanski and Ingielewicz 1995; Giatti 1996; Giatti 1997). In such applications, it is common to use a copolymer with perfluorinated side chains in combination with other polymers, such as anionic starch or carboxymethylcellulose (CMC) (Szymanski and Ingielewicz 1995; Giatti 1996; Giatti 1997; Kissa 2001).

The oil spread over the paper surface as shown in Figure 3, was observed from one hour to four hours. Oil droplet spreading has been reduced to some extent on the substrate and still largely sits as a sphere. This suggests that the paper and polymer coating have effectively acted as a barrier to restrict the flow of oil just by their surface properties. The small amount of oil that spread revealed the paper surface is difficult for oil to penetrate, and further confirms its low affinity for hydrocarbon-based liquids.

Keeping a sharp distinction between the droplet and background demonstrates surface tension effects on the coating ability to impede oil migration, and presumably acts as a successful barrier material. Furthermore, a barrier is needed in this case for making oil-proofing packaging papers. Yet, droplet volume loss and spreading tendencies should also be monitored during aging to truly judge the durability of the barrier.

These results indicates that under an optimized polymer coating choice, paper surfaces could be treated with effective oil resistance. Measurements of oil resistance were performed to evaluate the performance of polymer applied on paper surface. In this study, oil spreading and absorption were evaluated as dependent variables when different oil droplets were deposited on a paper. Figure 3 shows the barrier performance resulting from some polymer compositions on the paper surface: Figure 3-a shows the oil droplet remains in a distinct spherical form on the paper surface. This indicates that the polymer coating on the surface has created an effective hydrophobic barrier, preventing the oil from penetrating the paper. Additionally, Figure 3-b reprents the degree of oil spread demonstrates the barrier performance of the applied polymer. A slight spreading of the oil is observed, but the absorption remains minimal. Similar results were observed in studies by Chi et al. (2020), where polymer coatings such as polyethylene or biopolymer-based formulations significantly improved oil resistance. The slight spreading of the oil suggests that while the polymer provides some level of protection, its barrier efficiency is not absolute (Chi et al., 2020).

Additionally, Figure 3-c shows the circular wetting area around the oil droplet indicates that the polymer coating offers a relatively lower oil barrier effect. This suggests that the polymer formulation used was unable to provide adequate resistance on the paper surface. According to, inadequate surface coverage of polymers on paper leads to capillary absorption, compromising oil resistance. The larger spread observed in this image signals that the polymer barrier fails to form a uniform protective layer, which is critical for preventing oil penetration (Chi et al. 2020).

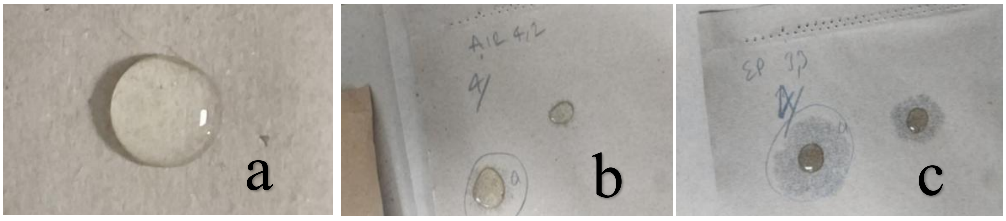

Figure 3. The Distribution of Oil Droplets on the Paper Surface (Representative Illustration)

These findings can be used to compare the effects of different polymer formulations on enhancing oil resistance on paper surfaces. The obtained results provide an important reference for determining the optimal formulation and optimizing production processes. The influence of polymer groups (A–E, defined in Table 1) on oil spread and penetration on paper substrates is shown in Figure 4.

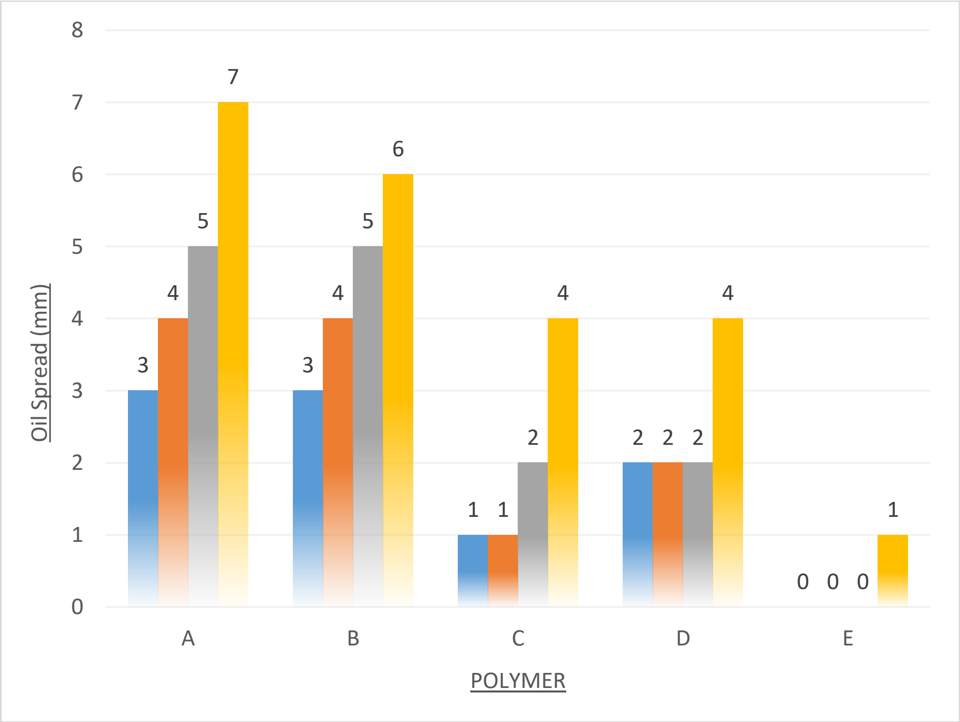

Figure 4. The Spreading Amounts of Polymer-coated 150 g/m² Papers After 1, 4, 8, and 12 h

Over time (after 1 h, 4 h, 8 h, and 12 h) of oil droppings on each polymer group resulted in an increase of oil spreading. This meant through time, less and further did the oil imbibe into the paper surface. The polymer group with the least oil resistance was Polymer A (maximum spread = 7 mm after 12 h on 150 g/m2 paper). It was discovered that this group was not good for oil proofing on the paper surface and hence designated as one of the least oil-resistant polymer. Polymer B had a much lower spread than polymer A (6 mm after the same exposure of 12 h). When compared, Polymer B appears to be more oil resistant than Polymer A, but still far away from what the other polymers could give. In Fig. 4 above, polymer C having an initial spread diameter of merely 1 mm after an hour shows lowest heading. Gradually the spread grew over time and peaked at a 4 mm after twelve hours. The performance of Polymer C seems to have moderate oil resistance. In contrast, Polymer D and E groups showed 0 mm relative to oil penetration (hence complete resistance to oil for the first hour) after one hour. There was a mild spread after 4 h and then spreaded to most 4 mm diameter after 12 h. It implies that Polymer D, E is the best group in term of oil resistance.

Mechanical Properties of Test Papers

Mechanical properties were evaluated to check the performance of test papers in the presence of applied polymer coatings. Multiple tests were performed on the tensile strength, burst strength, tear resistance, and stiffness evaluations of papers. Such properties are very important for the proper applicability of coated paper in practice, especially packaging papers that have high requirements in service properties and durability.

The data analysis reveals significant differences among the chemical treatment groups across all measured parameters, short-span compression test (SCT, Figure 5), including porosity (Figure 6), tensile strength (Figure 7), and bursting strength (Figure 8).

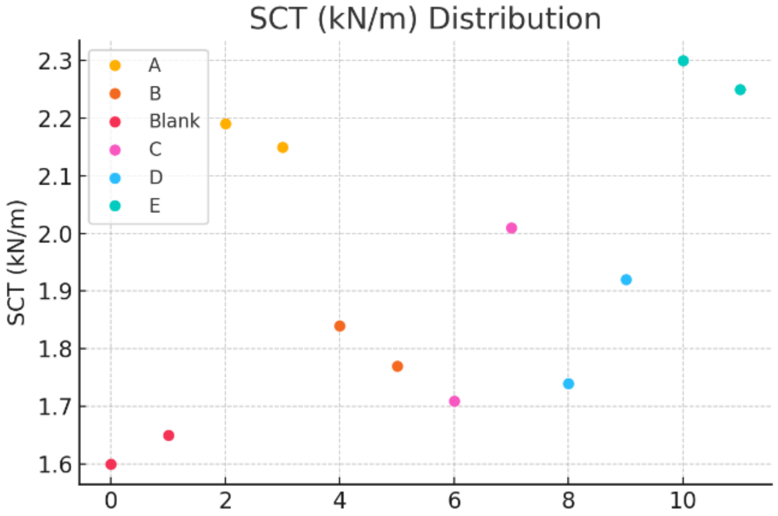

Figure 5. The Performance Values of SCT Obtained from the Algorithm as a Result of Test Processes

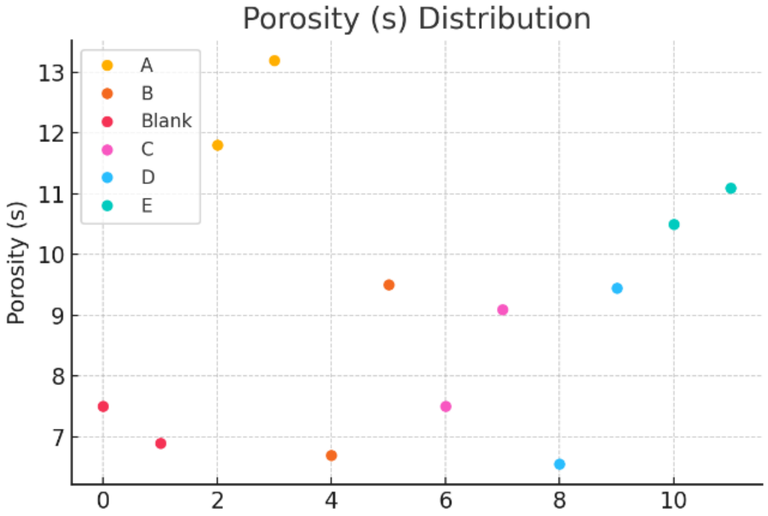

Figure 6. The Performance Values of Porosity Obtained from the Algorithm as a Result of Test Processes

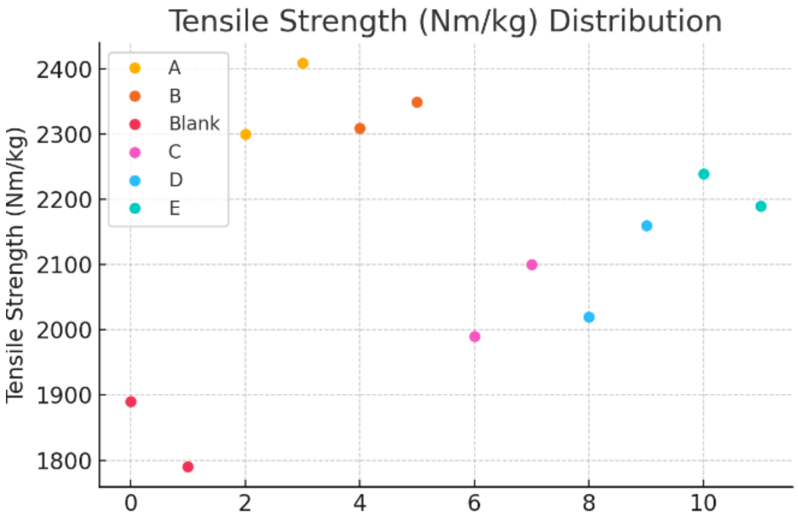

Figure 7. The Performance Values of Tensile Strength Obtained from the Algorithm as a Result of Test Processes

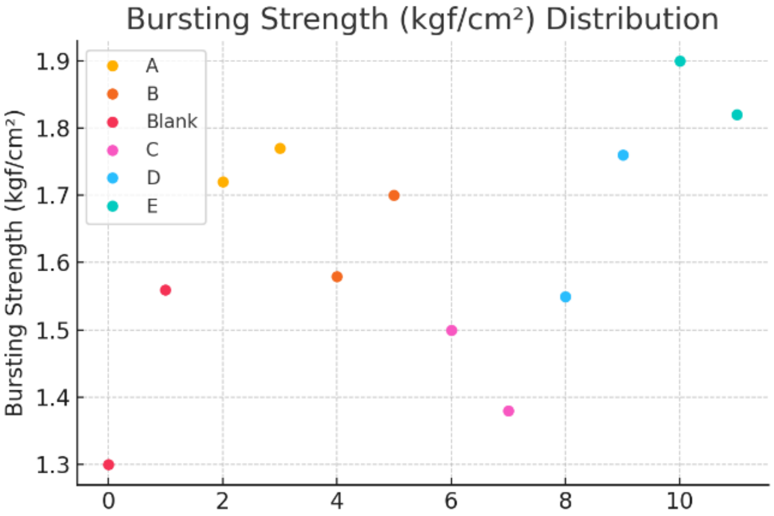

Figure 8. The Performance Values of Burst Strength Obtained from the Algorithm as a Result of Test Processes

Groups A (12.5 s) and E (10.8 s) exhibited the highest porosity values, indicative of enhanced fluid resistance, whereas the Blank (7.2 s) and B (8.1 s) groups demonstrated the lowest porosity, suggesting weaker structural integrity.

Regarding bursting strength, group E achieved the highest value (1.86 kgf/cm²), closely followed by group A (1.745 kgf/cm²), while the Blank (1.43 kgf/cm²) and C (1.44 kgf/cm²) groups recorded the lowest performance.

Similarly, SCT results showed superior resistance for groups E (2.275 kN/m) and A (2.17 kN/m), reflecting greater capacity to withstand compressive forces applied to the structure. The Blank group exhibited the weakest SCT performance (1.625 kN/m).

In terms of tensile strength, the highest mechanical durability was observed in groups A (2355 Nm/kg) and B (2330 Nm/kg), whereas the unnamed group (1840 Nm/kg) showed the lowest values. These findings underscore the efficacy of chemical treatments, particularly in groups A and E, in enhancing paper properties.

This observation aligns with Larsson et al. (2018), who reported a close correlation between SCT values, fiber compression, and chemical reinforcement. Overall, the Blank group consistently displayed the poorest mechanical performance, emphasizing the critical role of chemical treatment in substantially consolidating the paper structure.

Results of the analysis show that chemical treatments have great impact on the significant properties of paper (namely porosity, bursting strength, SCT, tensile strength). Porosity is the highest in A and E groups among all except is somewhat comparable with (Figure 6). Whereas chemically treated fibers were reported to be more fluid impervious with the enhanced fiber bond and decrease permeability at lower fluid pressure. This is in accordance with the lowest porosity values in the Blank group (7.2 s) untreated samples, and which showed that compaction and bonding are failed between untreated fibers collectively causing high value permeability.

Tensile strength is (Figure 7) another significant paper durability-measure, where the highest tensile strength is shown by A group (2355 Nm/kg) and B group (2330 Nm/kg). In a study agreed with these results but also cited “the extensive studies that showed the strong influence of chemical treatments on fiber cohesion and flexibility for increasing tensile strength. The worst performer (performance blank group, 1840 Nm/kg) one last time demonstrates that neat fibers have not enough mechanical durability to be required on an industrial scale (Mazega et al. 2022).

As for bursting strength (Fig. 8), a better performance of E (1.86 kgf/cm²) and A groups (1.745 kgf/cm²) is due to the chemical treatments which are aimed in improving inter-fiber bonding as extensively investigated in the literature. And the weakest results (1.43 kgf/cm²) are revealed from the Blank group and C group (1.44 kgf/cm²), which was similar to untreated samples with the low value fibre bonding and void in the system render lower strength (Rudi et al. 2018; Tanaka et al. 2018; Li et al. 2020; Uddin et al. 2024).

In general, Groups A and E outperformed the others in terms of both mechanical strength and oil barrier performance, highlighting the effectiveness of the applied chemical treatments over the untreated control. Interestingly, although Group E exhibited the lowest oil spreading area—indicating superior oil resistance—its mechanical performance was comparable to Group A, which showed the highest oil spread. This contrast suggests that oil barrier efficiency and mechanical strength do not always correlate directly, and different polymer characteristics may affect fiber bonding and surface barrier formation in distinct ways. Similar observations were reported by Chi et al. (2020), who noted that internal polymer diffusion and fiber–matrix interactions can significantly influence tensile strength, independent of surface repellency. Moreover, the results indicate that chemically treated groups like A and E could potentially be used interchangeably in certain applications, offering production flexibility without compromising performance. As proposed by Chi et al. (2020), future studies should also consider the environmental impact and cost-effectiveness of such treatments, in order to guide industrial-scale adoption.

Figure 9 shows that porosity yields a high positive correlation with SCT ($r = 0.83$), which means with more porosity better SCT performance was observed. Also, the porosity displays a moderate positive association with bursting strength (r = 0.66) and tensile strength (r = 0.69). There is a moderate correlation of bursting strength with SCT (r = 0.73) and tensile strength (r = 0.64) that is burst strength improvement also predictably comes with other properties improvements. Likewise, porosity has a significant positive relationship with SCT (r = 0.83) and weak although positive relationships to bursting strength (r = 0.73) and tensile (r = 0.60). Tensile strength is positively related to all parameters- porosity (r = 0.69), bursting strength (r = 0.64) and SCT (r = 0.65) in moderate manner lastly. The correlation analysis was conducted using the Pearson correlation coefficient to assess the strength and direction of linear relationships between the selected physical and mechanical parameters: porosity, tensile strength, short-span compression test (SCT), and burst strength. The data used for correlation calculations were obtained as average values from each of the five polymer-treated paper groups (A–E). Calculations and visualizations (Figure 9) were performed using Microsoft Excel 2016. The correlation strength was interpreted as follows: weak (r < 0.5), moderate (0.5 ≤ r < 0.75), and strong (r ≥ 0.75).

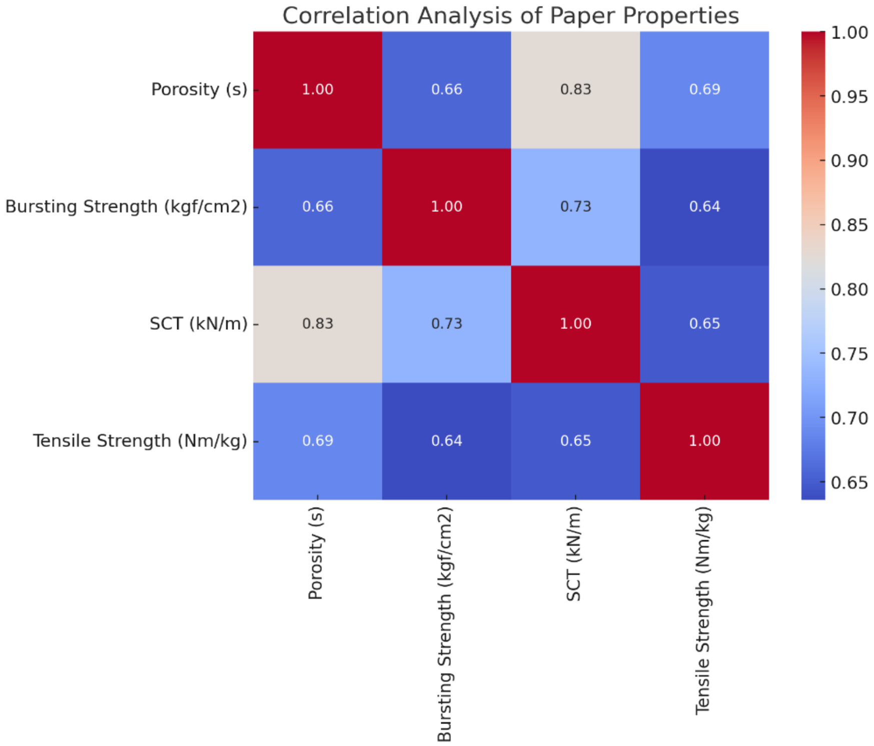

Figure 9. Significant Parameters Correlations are Shown on the Correlation Analysis

Overview of chemical replacements, where A and E substitutions have a fairly similar overall rating especially in porosity, SCT and tensile strength (meaning that E could easily replace A is some cases). The B group offers balance and C is action, both in tensile as well as bursting strength so B can stand in for C or either can be substituted with B as it is price and availability dependent. As opposed to the Blank group is a clear fail complete list, with blank samples being never be an appropriate alternative to chemically processed. To sum up, the high degree of correlation between porosity and SCT are two significant aspects to consider when indicating paper quality. Production flexibility given by A and E groups similar performance enables them to be employed as replaceable to desired paper properties thus optimized the resource utilization.

The findings throughout this study found strong relationships between porosity, SCT, bursting strength, and tensile strength in the paper samples investigated. As Larsson et al. (2018) suggested, We found a highly significant positive relationship between porosity and SCT (r = 0.83) meaning that porous values tend to enhance resistance of the material to compression loading. This could stem from internal bonding between fibers being improved, and that will make the paper sound. A moderate correlation of porosity (r = 0.66) with bursting strength and (r = 0.69) tensile strength have been reported which is in consistency with the reports in terms of mechanical strength via porosity. Porosity, however, which in general is taken as measure of permeability also gives an idea of how much fiber compaction, we have thereby affecting directly the resistance the paper to mechanical forces. Additionally, burst strength was associated with moderate SCT (r = 0.73) and tensile strength (r = 0.64) in those charts, indicating the relationship obtained for these mechanical properties. In a similar study for bursting strength showed that it was positively associated with tensile durability for higher level of bonding among fibers within paper matrix (Uddin et al. 2024). For the duration across chemical treatments, trends in porosity and SCT/E showed similarity between A and E groups but E could be used as a substitute for A without any loss in quality findings are consistent with (Tanaka et al. 2018), other study both showed that the chemical optimization under controlled conditions resulted in similar mechanical performance across different treatment groups. Low performance by B and C groups, moderate value indicates their potential as trade-off components with a particular aim on certain mechanical requirement.

On the other hand, untreated samples (Blank group) showed lower trends across all variables measured; the studies from (Rudi et al. 2018) limitation on the treated fibers thereby not able to increase more significantly strength for paper durability as per chemical treatments were proven to enhance fiber bonding and reduction of voids which is closely predicted mechanical performance (Chi et al. 2020). With these robust associations, especially that which one observes for porosity and SCT in other words they be honest markers of paper quality. The homogeneity of A and E chemical treatments activity offer recognised production flexibility, in favour of resource shift and cost-efficient material utilization. Follow-up investigations are required to elucidate the economical consequences and the ecological of treatments so as to establish their industrial feasibility.

DISCUSSION

This study reveals considerable diversity in oil resistance and mechanical performance among different polymer classes coated on paper substrates. Polymers D and E exhibited the highest oil resistance, with no initial spreading and a small increase (maximum of 4 mm) over 12 h. The polymer C exhibited limited oil resistance as the extent oil spread only reached 4 mm at the end of 60 min. In contrast, Polymers A and B showed the least oil resistances for spreads of 7 mm and 6 mm after 12 h, respectively. The data reveal that Polymers D and E produces greater oil barrier performance, whereas A and B offer less oil resistance for oil-resistant applications. Analysis of results also identifies substantial mechanical variations of the paper samples with regards treatment by various chemical groups in place. The polymers A and E are the two polymers which possess exceptional mechanical performance due their porosity values (125 s; 108 s) and SCT values (2.17 kN/m for A leading to B 2.275 kN/m respectively). This shows load-bearing compressions are notably more resistant. But the tensile strength of Polymer A (2355 Nm/kg) and Polymer B (2330) further indicate a better durability of material. In contrast, Blank showed the weakest mechanical properties characterized by high porosity

(7.2 s), low SCT (1.625 kN/m), and lowest tensile strength (1840 Nm/kg). To sum up, Polymers A and E exhibit both superior mechanical strength and excellent oil barrier properties, making them strong candidates for use in demanding paper-based packaging applications. Further optimization of polymer formulations and coating techniques is required to achieve enhanced oil resistance in such applications.

As presented by Mazega et al. (2022) severe enhancement in barrier properties can be achieved by multi-layer coatings or hybrid polymers. Biopolymer alternatives (e.g., chitosan or cellulose derivatives) for oil resistance which could better the protection without compromising environmental sustainability will be investigated in further studies. As it is seen from a wide survey about oil resistance and the mechanical properties of the chemically treated specimens of paper, Polymers D and E proved being the best suited papers for applications with both high oil resistance and high mechanical performance. The barrier properties of oil penetration were high (up to 4 mm over 12 h of oil spreading) by the low oil-spread polymers. Furthermore, their high mechanical properties (SCT values of 2.275 kN/m in case of E) and tensile strength ranging from 2190 to 2240 Nm/kg make them are well suited for critical applications that need mechanical longevity. On the other hand, polymers A and B exhibited poorer oil resistance with significant spreading after 12 h (6-7 mm) though Polymer A was strong in the tensile strength (2355 Nm/kg). Polymer D and E are the most favourable options for situations where oil barrier performance and mechanical durability is necessary, with Polymer A may be considered for applications where tensile strength is more important than oil resistance.

Future studies should aim at the optimization of polymer formulations to further boost performance while solving the recyclability as well as sustainability issues. Bio-based polymers and composites alternatives have very high potential, which can be used for the development of the next generation of paper products that will ensure a combination of high performance and environmental responsibility.

CONCLUSIONS

The effects of polymer coatings on resistance to oil and paper surface mechanical properties are analysed in this study, where it was established that the nature of the polymer has a pronounced effect on both.

Groups of polymers D and E exhibited the highest oil resistance, achieving complete resistance in the first hour and the extent of spread of oil limited to 4 mm after 12 h. These two properties were moderate in Groups A and B, and least effective in Group C. Regarding mechanical performance, groups A and E showed higher values in porosity, bursting strength, SCT, and tensile strength. Thus suitable to ensure maximum enhancement towards both durability and functionality. This result highlights the contribution of polymer coatings to improved barrier performance and mechanical integrity of the paper, leading to its suitability for applications in advanced packaging.

Future studies may focus on the long-term migration behavior of these polymers under various storage and temperature conditions, as well as their recyclability and biodegradability in real-life food packaging environments.

ACKNOWLEDGEMENTS

This study was conducted by the R&D Center of Kahramanmaraş Paper Factory. The author would like to thank the R&D center staff for their contributions. The author worked on this project as a scholar under the TÜBİTAK 2244 program, supported by grant number 118C060.

AUTHOR CONTRIBUTIONS

Only one author contributed to this study.

FUNDING STATEMENT

This study was supported by the TÜBİTAK 2244 program with the grant number 118C060.

CONFLICT OF INTEREST STATEMENT

The author declare no conflict of interest.

ETHICS COMMITTEE APPROVAL

This study does not require any ethics committee approval.

REFERENCES

Basak, S., Dangate, M. S., and Samy, S. (2024). Oil- and water-resistant paper coatings: A review. *Progress in Organic Coatings*, 186, 107938. Doi:10.1016/j.porgcoat.2023.107938

Billmers, R. L., Mackewicz, V. L., and Trksak, R. M. (2004). U.S. Patent No. 6,790, 270. Washington, DC: U.S. Patent and Trademark Office.

Chi, K., Wang, H., and Catchmark, J. M. (2020). Sustainable starch-based barrier coatings for packaging applications. *Food Hydrocolloids*, 103, 105696.

Cui, H. C., Li, D. C., and Li, J. L. (2011). Theoretical research on fluorocarbon surfactant of fluorocarbon-based magnetic fluid. *Advanced Materials Research*, 211, 82-86.

Giatti, R. (1996). New fluorochemicals for greaseproof papers. *Paper Technol*, 37(9), 49-54.

Giatti, R. (1997). Greaseproof alternative offers eco-advantage. *Pulp Paper Europe*, 2(2), 25-27.

Glenn, G., Shogren, R., Jin, X., Orts, W., Hart-Cooper, W., and Olson, L. (2021). Per-and polyfluoroalkyl substances and their alternatives in paper food packaging. *Comprehensive Reviews in Food Science and Food Safety*, 20(3), 2596-2625.

Hossain, R., Tajvidi, M., Bousfield, D., and Gardner, D. J. (2022). Recyclable grease-proof cellulose nanocomposites with enhanced water resistance for food serving applications. *Cellulose*, 29(10), 5623-5643.

Hubbe, M. A., and Pruszynski, P. (2020). Greaseproof paper products: A review emphasizing ecofriendly approaches. *BioResources*, 15(1), 1978-2004.

Jung, H., Kwon, J., Jung, H., Cho, K., Yu, S., Lee, S., Jeon, M., and Im, S. (2022). Short-chain fluorocarbon-based polymeric coating with excellent nonwetting ability against chemical warfare agents. *RSC Advances*, 12, 7773-7779. Doi:10.1039/d1ra08326k.

Kissa, E. (2001). *Fluorinated Surfactants and Repellents*. Revised and Expanded, Marcel Dekker, New York, NY.

Kjellgren, H., and Engstrom, G. (2005). The relationship between energy requirement and barrier properties in the production of greaseproof paper. *TAPPI J*, 4(8), 7-11.

Ladd, E. (2012). *The Design and Synthesis of Dendrimers for Applications in the Pulp and Paper Industry*. McGill University, Canada.

Larsson, P., Lindström, T., Carlsson, L., and Fellers, C. (2018). Fiber length and bonding effects on tensile strength and toughness of kraft paper. *Journal of Materials Science*, 53, 3006-3015. Doi: 10.1007/s10853-017-1683-4.

Lee, W., Kim, H., and Park, J. (2015). Mechanical properties of paper: Influence of porosity. *Journal of Industrial Materials,* 19(2), 345-356.

Li, C., Fu, Y., Wang, B., Zhang, W., Bai, Y., Zhang, L., and Qi, L. (2020). Effect of pore structure on mechanical and tribological properties of paper-based friction materials. *Tribology International*, 148, 106307. Doi:10.1016/j.triboint.2020.106307.

Mazega, A., Tarrés, Q., Aguado, R., Pelach, M., Mutjé, P., Ferreira, P., and Delgado-Aguilar, M. (2022). Improving the barrier properties of paper to moisture, air, and grease with nanocellulose-based coating suspensions. *Nanomaterials*, 12. https://doi.org/10.3390/nano12203675.

Rudi, H., Ghorbannazhad, P., and Hubbe, M. (2018). Optimizing the mechanical properties of papers reinforced with refining and layer-by-layer treated recycled fibers using response surface methodology. *Carbohydrate Polymers*, 200, 391-399. Doi:10.1016/j.carbpol.2018.08.006.

Schaider, L. A., Balan, S. A., Blum, A., Andrews, D. Q., Strynar, M. J., Dickinson, M. E., Lunderberg, D. M., Lang, J. R., and Peaslee, G. F. (2017). Fluorinated compounds in US fast food packaging. *Environ. Sci. Technol. Lett,* 4(3), 105-111. Doi: 10.1021/acs.estlett.6b00435.

Sharif, R., Mohsin, M., Qutab, H. G., Saleem, F., Bano, S., Nasir, R., and Wahlah, A. (2023). Durable water and oil repellents along with green chemistries: an overview. *Chemical Papers*, 77(7), 3547-3560.

Sharma, R., Verma, S., and Gupta, N. (2019). Optimization of paper properties through chemical treatments. *Industrial Pulp Research*, 10(6), 788-793.

Szymanski, A., and Ingielewicz, H. (1995). Possibilities for energy savings in the production of greaseproof papers. *Przeglad Papeiriniczy*, 51(3), 114-118.

Tanaka, A., Khakalo, A., Hauru, L., Korpela, A., and Orelma, H. (2018). Conversion of paper to film by ionic liquids: Manufacturing process and properties. *Cellulose*, 25, 6107-6119. Doi:10.1007/s10570-018-1944-7.

TAPPI T 441 (2021). *Water absorptiveness of sized (non-bibulous) paper, board, and paperboard (Cobb test)*. Technical Association of the Pulp and Paper Industry, Atlanta, GA. https://www.tappi.org

TAPPI T 559 cm-12 (2022). *Grease resistance test for paper and paperboard*. Technical Association of the Pulp and Paper Industry, Atlanta, GA.

Tayeb, H. A., Tajvidi, M., and Bousfield, D. (2020). Based oil barrier packaging using lignin-containing cellulose nanofibrils. *Molecules*, 25(6), 1344.

Uddin, M., Likhon, M., Rahman, M., and Jahan, M. (2024). Effect of fibre-quality parameters on pulp properties by using multiple linear regression and artificial neural network. *International Wood Products Journal*, *15*(2-4), 91-99.

Wang, S., Pei, L., Wei, J., Xie, J., Ji, X., Wang, Y., Jia, P., and Jiao, Y. (2024). Preparation of environmentally friendly oil- and water-resistant paper using holo-lignocellulosic nanofibril (lcnf)-based composite coating. *Polymers,* 16. Doi:10.3390/polym16081078.

Wang, Z. Y., Cousins, I. T., Scheringer, M., and Hungerbuhler, K. (2013). Fluorinated alternatives to long-chain perfluoroalkyl carboxylic acids (PFCAs), perfluoroalkane sulfonic acids (PFSAs) and their potential precursors. *Environ. Int*, 60, 242-248. Doi: 10.1016/j.envint.2013.08.021.

Wei, L., Demir, T., Grant, A., Tsukruk, V., Brown, P., and Luzinov, I. (2018). Attainment of water and oil repellency for engineering thermoplastics without long-chain perfluoroalkyls: Perfluoropolyether-based triblock polyester additives. *Langmuir: The ACS Journal of Surfaces and Colloids*, 34(43), 12934-12946. Doi: 10.1021/acs.langmuir.8b02628.

Yamaguchi, H., and Yaguchi, T. (1996). *Fiber beating with enzyme pretreatment*. In: 50th Appita Annual General Conference Proceedings. APPITA, 1, 91-96.