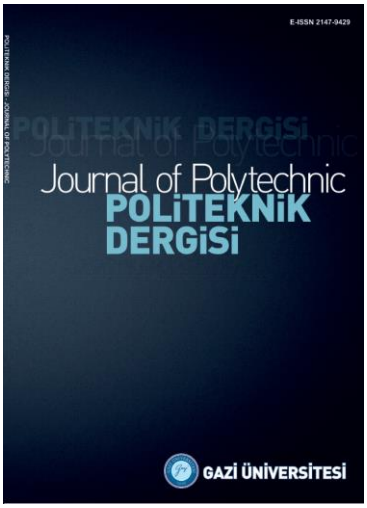

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Effect of disintegration time and temperature on the structural properties of recycled industrial waste paper: an experimental analysis

Endüstriyel atık kağıtların geri dönüşümünde parçalanma süresi ve sıcaklığın yapısal özelliklere etkisi: deneysel bir analiz

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Effect of Disintegration Time and Temperature on the Structural Properties of Recycled Industrial Waste Paper: An Experimental Analysis

Highlights

- *Effect of disintegration time and temperature on recycled industrial waste paper was investigated.*
- *20 sample groups were analyzed using brightness, surface, and air permeability metrics.*
- *30 min at 40 °C yielded highest brightness and best surface quality.*
- *Excessive time or high temperature (60 °C) caused fiber degradation.*
- *Results support energy-efficient recycling in paper production.*

Graphical Abstract

The study examines the structural and optical performance of recycled waste paper under different disintegration times and temperatures. The optimum performance was achieved at 30 minutes and 40 °C Times New roman, 10

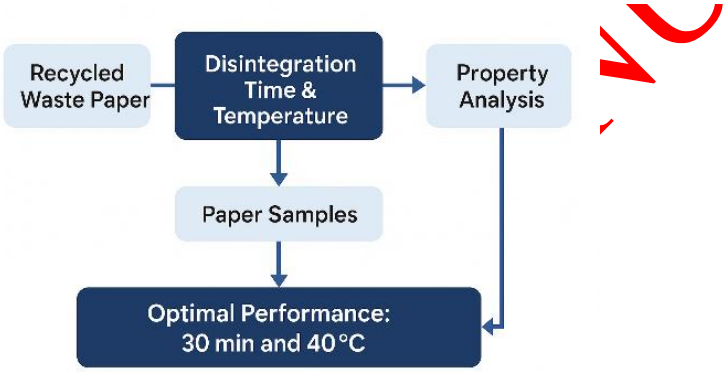

Figure. Experimental Workflow for Optimizing Recycled Paper Quality

Aim

To investigate how disintegration time and temperature affect the quality of recycled paper.

Design & Methodology

Experimental paper samples were prepared from waste fibers using different durations and temperatures, followed by physical and optical property analyses.

Originality

This study uniquely evaluates the impact of combined disintegration time and temperature variables in recycled paper processing.

Findings

Optimal paper quality (high brightness, low air permeability, smooth surface) was achieved at 30 minutes and 40 °C. Extended processing reduced quality.

Conclusion

Moderate disintegration time and temperature enhance recycled paper quality while ensuring energy efficiency. Results are valuable for sustainable paper production.

Declaration of Ethical Standards

The author of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Effect of Disintegration Time and Temperature on the Structural Properties of Recycled Industrial Waste Paper: An Experimental Analysis

Araştırma Makalesi / Research Article

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ABSTRACT

The present study investigates the impact of disintegration time and processing temperature on the structural and optical properties of papers manufactured from recycled industrial waste. The papers were subjected to five disintegration durations at four temperatures, thus yielding 20 experimental groups. The analysis encompasses pivotal parameters such as basis weight, surface smoothness, and brightness.

The findings indicate that a 30-minute disintegration time at 40 degrees Celsius provides optimal conditions, yielding high brightness (L*=90.43), low air permeability (6.11 µm/min), and uniform surface properties (3,887 µl/min). The commencement of a 60-minute disintegration period resulted in a decline in optical quality, brightness (L*=87.54), and gloss (33%). It has been demonstrated that an increase in temperature of up to 40 degrees Celsius has a beneficial effect on fibre distribution. It was demonstrated that at 60 degrees Celsius, there was a negative impact on surface characteristics.

The study hypothesises that 30–40 minutes of disintegration at 40 degrees Celsius is optimal for the production of recycled paper. The efficacy of these parameters in enhancing energy and resource efficiency in recycling processes has been demonstrated. Further exploration is recommended, with different fibre blends and chemical additives to enhance material performance.

Keywords:Structural properties, Recycled paper waste, Optical properties, Resource efficiency, Cellulose fiber degradation

Endüstriyel Atık Kağıtların Geri Dönüşümünde Parçalanma Süresi ve Sıcaklığın Yapısal Özelliklere Etkisi: Deneysel Bir Analiz

ÖZ

Bu çalışma, endüstriyel atık kağıtların geri dönüşümü sırasında parçalanma süresi ve sıcaklığın; üretilen kağıtların yapısal ve optik özelliklerine etkisini incelemektedir. Deneylerde atık kağıtlar 5 farklı parçalanma süresinde ve 4 farklı sıcaklıkta işlenerek 20 numune grubu oluşturulmuştur. Numunelerde gramaj, yüzey düzgünlüğü, hava geçirgenliği, kontak açısı, parlaklık (L*), renk koordinatları (a*, b*) ve renk farkı (ΔE) değerleri analiz edilmiştir.

Sonuçlar, 30 dakikalık parçalanma süresi ve 40°C sıcaklığın optimum koşullar olduğunu göstermiştir. Bu parametrelerde hazırlanan numuneler yüksek parlaklık (L*=90.43), düşük hava geçirgenliği (6.11 µm/pas) ve homojen yüzey özellikleri (3.887 ml/min) sergilemiştir. Uzun süreli (60 dk) işlemlerde ise optik kalite düşmüş, L* değeri 87.54'e gerilemiş ve %33 gloss kaybı gözlenmiştir. Ayrıca, sıcaklık artışı 40°C'ye kadar lif dağılımını optimize ederken, 60°C yüzey özelliklerini olumsuz etkilemiştir.

Bu çalışma, geri dönüştürülmüş kağıt üretiminde 30-40 dakika parçalanma süresi ve 40°C işlem sıcaklığının en uygun parametreler olduğunu ortaya koymaktadır. Bu bulgular, geri dönüşümde enerji ve kaynak verimliliğini artıracak parametrelerin belirlenmesi açısından önemlidir Malzeme performansının daha da iyileştirilmesi için, gelecekte farklı lif karışımları ve kimyasal katkıların etkisinin araştırılması önerilmektedir.

Anahtar Kelimeler: Yapısal özellikler, Geri dönüştürülmüş kağıt atığı, Optik özellikler, Kaynak verimliliği, Selüloz lif bozunması

1. INTRODUCTION

The paper and paper products manufacturing industry is structurally fragmented, comprising a wide array of small and medium-sized enterprises (SMEs) that specialize in diverse product lines such as specialty papers, packaging materials, hygiene products, and industrial applications. These enterprises typically operate independently, focusing on specific product groups and catering to distinct market segments [1]. Paper, in one form or another, is present in nearly every aspect of daily life [2]. As a versatile material, it plays an indispensable role in modern living—not only in its primary function of communication through writing and printing but also in industrial filtration, as a carrier substrate, and in the construction sector as an insulation or decorative surface material. Particularly within the printing industry, it is essential for the production of books, catalogues, periodicals, branding materials, labels, and packaging [3]. Beyond this, paper provides effective packaging and cleaning solutions across a wide range of applications, from sanitary products to food packaging. This remarkable versatility, when coupled with its recyclable

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and eco-friendly characteristics, makes paper an irreplaceable material in both industrial and consumer contexts.

In the modern era, the dynamics of globalization, industrialization, and urbanization have led to a marked increase in the consumption of natural resources. This trend has not only accelerated resource depletion but also triggered uncontrolled waste generation, ultimately disrupting environmental equilibrium [4]. Consequently, recycling—defined as the collection, reprocessing, and reintegration of post-consumer materials into the production cycle—has emerged as a strategic priority in line with sustainable development objectives, aiming to reduce raw material demand and enhance resource efficiency.

Empirical studies demonstrate that paper ranks among the materials with the highest recycling performance. The benefits of paper recycling are substantial: reductions in air emissions by 74–94%, a 35% decrease in water pollution load, and approximately 45% savings in water consumption. Furthermore, reintegrating one metric ton of waste paper into the production process prevents the felling of nearly eight mature trees. These figures underscore the pivotal role of recycling in environmental sustainability while highlighting its potential as a highly cost-effective investment in the long term [5].

Recycling also emerges as a critical mechanism for economic recovery, with waste paper reclamation playing a significant role in reducing environmental pollution [6-9]. However, an important caveat must be acknowledged regarding the recyclability of paper. The fibrous plant-based structure that forms the basis of paper degrades with each recycling cycle. This degradation manifests in several ways, including fiber shortening, structural damage to cell walls, reduced water retention capacity, decreased fibrillation, and weakened inter-fiber bonding. These physicochemical changes progressively erode the functional properties of the fibers. The extent to which the original characteristics of the fibers can be preserved directly affects the quality of the recycled paper produced. Consequently, the contribution of recycled fibers to new paper production is closely linked to the degree of preservation of their intrinsic qualities [10].

Recent literature suggests that cellulose fibers can endure a maximum of five to six recycling cycles before their structural integrity declines beyond usability. Nevertheless, even the recovery of a single fiber up to five times yields considerable environmental and economic benefits, including:

- Reduced consumption of natural resources
- Decrease in greenhouse gas emissions
- Lower demand for landfill space
- Significant energy savings compared to virgin production
- Cost reduction in manufacturing
- Contribution to circular economy frameworks
- Alignment with sustainable development goals
- Safeguarding of resources for future generations

This study systematically explores current recycling trends and methodologies aimed at enhancing sustainability. Sustainability itself represents a multidisciplinary framework, addressing resource efficiency, ecological balance, and the intensifying pressures of population growth, climate change, and urbanization. Paper, as a recyclable material derived from renewable lignocellulosic biomass, fits naturally within this framework. Its appeal lies in several features: it originates from bio-based, sustainable raw materials; offers a favorable cost-to-performance ratio; combines light weight with mechanical strength; and is inherently biodegradable.

Recent research across various industrial sectors has highlighted the critical role of temperature and processing time in determining surface properties and color stability. In particular, studies on printing and surface finishing technologies emphasize the influence of temperature–time parameters on optical characteristics [11–12]. Moreover, the use of eco-friendly dyes and pigments derived from microorganisms has been reported to open new possibilities for surface coating and enhanced color stability [12–13]. Within this context, optimizing variables such as temperature and duration represents a crucial step not only for paper production but also for a broad range of material systems.

In the packaging industry, innovative solutions aimed at minimizing environmental footprints are being developed in line with life cycle assessment (LCA) principles [15]. Advanced technological approaches—such as nanotechnological modifications and barrier coatings—have gained significant attention for their ability to enhance the functional properties of paper-based packaging materials.

The paper manufacturing process represents an industrial model that comprehensively integrates the principles of sustainable development. Through carbon-neutral production systems, high recycling rates, and closed-loop operations, the paper industry not only contributes to environmental sustainability but also plays a significant role in supporting rural economies. These characteristics position the sector as a leading example of sustainable production [16]. By sourcing raw materials from forests managed under sustainable forestry practices, the paper industry does not contribute to deforestation; rather, it supports forest expansion through controlled harvesting and systematic reforestation programs. International certification systems such as the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC) serve as key mechanisms ensuring compliance with these sustainability principles. Contemporary sustainable forestry practices are structured around ISO 14001 standards and Sustainable Forest Management (SFM) criteria. Within this framework, harvesting plans are developed based on stock assessments and growth models, ensuring that for every tree felled, at least one seedling is planted, and certification is carried out in accordance with

internationally recognized standards such as FSC or PEFC [17].

Efficiency in paper recycling processes is strongly influenced by the homogeneity of the input material. Research indicates that processing waste papers of the same category together helps maintain fiber length distribution, reduces contamination risk, minimizes the need for chemical additives, and enhances energy efficiency [18]. Achieving a successful recycling process largely depends on grouping similar paper types and processing them within the same production line [19]. Consequently, effective classification protocols implemented during waste management are among the key determinants of a circular recycling economy [20].

Waste papers can be classified based on several criteria, including sheet structure, manufacturing technique, and the additives employed (such as fillers and surface coatings). Paper and board products suitable for recycling are typically organized into five main categories according to their quality and structural characteristics. Each category requires specific recycling parameters and process optimization strategies. The classification outlined in Table 1 is essential for reintegrating waste paper into the production cycle with maximum efficiency [21].

Table 1. Categories of Recyclable Paper [22]

Paper Category	Description	Application Area
Mixed Office Waste (MOW)	A heterogeneous mixture of papers collected from households and offices, produced using both mechanical and chemical pulps; includes manufacturing offcuts.	Production of cardboard boxes, packaging materials
Old Newspapers (ONP)	Printed materials, primarily newspapers, with high mechanical pulp content.	Newspaper production, insulation boards
Old Corrugated Containers (OCC)	Used corrugated cardboard collected from retail, industrial, and office settings.	Box production, packaging
Mill Broke	White and colored paper waste generated during paper production, not subjected to printing; also includes rejected materials from recycling facilities.	White/colored paper manufacturing, colored tissue production
Printed Waste Paper	Any paper products with printed surfaces, including books, magazines, and office prints.	White/colored paper manufacturing, tissue production

2. MATERIAL and METHOD

2.1. Materials

This study utilized cutting scraps generated during the paper production process. These waste materials, referred to as secondary fibers, consist of trimmings from both printed and unprinted paper [23]. The key physical and optical properties of the selected waste papers—including moisture content, lightfastness, grammage, and surface smoothness—are detailed in Table 2. It is crucial to note that all waste paper samples were derived from a single production line and batch, thereby ensuring uniformity in fibre composition and minimising variability between experimental groups. It is important to note that no additional bleaching or chemical treatment was applied prior to processing.

2.2. Methodology

Fibers of identical grammage were disintegrated and suspended in a 7000 mL water bath under standardized processing conditions. The resulting fiber suspension was converted into paper sheets using a conventional wire mesh and the immersion sheet-forming technique. Fibers were subjected to mechanical disintegration for 5, 10, 15, 30, and 60 minutes, respectively. For each disintegration group, samples were further conditioned in hot water at temperatures of 30, 40, 50, and 60 °C. These varying combinations of treatment time and temperature allowed for a systematic comparative analysis of fiber behavior and sheet properties.

In order to guarantee replicability, it was imperative to exercise stringent control and monitoring of the environmental conditions (water temperature, pH, and ambient humidity) during the course of each trial. Prior to the commencement of the experimental phase, the equipment, inclusive of the blender, the sheet-forming frame, and the measurement devices, underwent a process of calibration. Each treatment was conducted in three distinct runs, and measurements for physical and optical properties were obtained from multiple points on each sheet to account for within-sample variation.

2.2.1. Pulp preparation from paper mill waste

Paper mill scraps with a grammage of 30 g/m² were used as the raw material in this study. The experimental procedure involved the following steps:

- Waste papers were first shredded into smaller pieces and placed in a blender for each experimental group.
- 1000 mL of boiling water (approx. 100 °C) was added to the blender.
- Paper samples were soaked in the hot water for different durations: 5, 10, 15, 30, and 60 minutes.
- After the specified soaking period, samples were disintegrated in a 1000 W blender at speed setting "2" for 3 minutes to obtain a fibrous pulp.
- The prepared pulp was then used to produce paper sheets via immersion sheet forming.

2.2.2. Sheet formation from processed waste fibers

The fibrous pulp obtained through blending was transferred into a sheet-forming vat with internal dimensions of 27 × 40 cm and a capacity of

Table 2. Properties of Paper Mill Waste Used as Raw Material

Grammage	Surface Smoothness	Air Permeability	Contact Angle	Color Coordinates					Gloss			
g/m²	ml/min	µm/pas	°	L	a	b	Gloss	Color	L	a	b	ΔE
41.2	549	2,95	75.0	91.2	1.33	11.9	15.8		84.6	3.5	29.7	19.56

approximately 30 liters. For each batch, 7000 mL of water was added. Water temperature was carefully adjusted and controlled for each sample group at 30, 40, 50, and 60 °C, respectively. This stage was crucial for observing how thermal variation affects fiber behavior during sheet formation. 19 × 25 cm metal wire screen was used to form sheets. For each combination of disintegration time and temperature, a corresponding paper sheet was produced by immersing the screen into the pulp suspension.

2.2.3. Color measurement

The optical properties—color and gloss—of the fabricated paper samples were evaluated in accordance with the CIELAB color space. Measurements were performed using a Konica Minolta CM-700d spectrophotometer, under D65 daylight illumination and with a 10° standard observer configuration [24–25]. After drying, each sample's L*, a*, b* color values and gloss levels were recorded.

Following exposure to a lightfastness test, the same parameters were measured again to assess changes in color. Color differences before and after exposure were calculated using the CIELAB-based total color difference formula, yielding ΔE* values. The equations used for these calculations are provided below:

$$\Delta E^*ab = \sqrt{[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]} \quad (1)$$

$$\Delta L^* = (L^*_2 - L^*_1) \quad (2)$$

$$\Delta a^* = (a^*_2 - a^*_1) \quad (3)$$

$$\Delta b^* = (b^*_2 - b^*_1) \quad (4)$$

In this system, L* represents the lightness-darkness axis, a* the red-green axis, and b* the yellow-blue axis. Gloss corresponds to surface shine. As ΔE* increases, the perceived difference in color becomes more pronounced. All corresponding values, including gloss levels and color differences, are presented in Table 4, and a graphical representation of the CIELAB color space is provided in Figure 1.

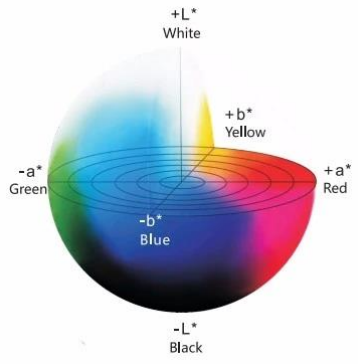

Figure 1. Color Universe

2.2.4. Surface smoothness measurement

The smoothness properties of the paper surface were assessed using the Bendtsen method, as described in the Scan-P 21 TAPPI UM 535 [26] standard. A Lorentzen & Wettre Bendtsen testing apparatus was employed, operating under a constant air pressure of 98 kPa. The outcomes of these tests are presented in Table 5. Conducted in full accordance with the prescribed protocol, this method enables a quantitative evaluation of the relationship between air permeability and surface smoothness on the paper substrate.

2.2.5. Air permeability measurement

Air permeability was determined following the ISO 5636-3 standard, which outlines procedures for measuring the flow rate of air passing through a defined area of paper or paperboard under a specific pressure differential. The measurements can be conducted using any apparatus that complies with the requirements stipulated in ISO 5636. During the test, a sample is clamped between a circular gasket and a flat, circular surface of known dimensions. One side of the sample is exposed to ambient atmospheric pressure, while a slightly reduced yet stable pressure is maintained on the other side throughout the measurement process [27].

2.2.6. Contact angle measurement

The contact angle describes the angle formed at the interface between a liquid droplet and a solid surface, serving as a critical indicator of surface wettability and surface energy. Experimental findings suggest that a high contact angle signifies a hydrophobic surface character and high surface tension, whereas values approaching 0° are indicative of a hydrophilic surface with low surface tension [28]. In order to investigate changes in the contact angle of the paper samples, measurements were carried out using a PGX+ portable tensiometer (goniometer). To determine the hydrophobic nature of the paper surface, 3 µL droplets of distilled water were gently placed on the natural, horizontal fiber direction of the sample using the goniometer, and static contact angles were recorded under controlled conditions [29]. Data were captured at a rate of 200 frames per minute, and the results are documented in Tables 4 and 5. Variations in contact angles were further illustrated through droplet shape analysis.

2.2.7. Lightfastness Measurement

Lightfastness was evaluated in accordance with the TS 1008 EN ISO 105-B02 standard [28, 30], using the Solarbox 1500E device and blue wool reference standards. The total color difference (Δe*) between exposed and unexposed samples was assessed using a spectrophotometric method to quantify the extent of color change resulting from light exposure.

3. FINDINGS

This section presents the findings obtained from colorimetric analyses and lightfastness tests conducted on paper samples prepared under varying temperatures and holding durations. The specific preparation parameters used during sample processing are outlined in Table 3. Corresponding color measurement results and lightfastness values for each sample are detailed in Table 4.

Table 3. Sample Preparation Parameters

Sample	Holding Duration	Water Used for Pulping	Drained Water	Machine Speed	Disintegration Time	Water in Pulp Tank
	min	mL (100 C°)	C°	w	min	mL
WS - 1	5	1000	30	1000	3	7000
WS - 2			40			
WS - 3			50			
WS - 4			60			
WS - 5	10	1000	30	1000	3	7000
WS - 6			40			
WS - 7			50			
WS - 8			60			
WS - 9	15	1000	30	1000	3	7000
WS - 10			40			
WS - 11			50			
WS - 12			60			
WS - 13	30	1000	30	1000	3	7000
WS - 14			40			
WS - 15			50			
WS - 16			60			
WS - 17	60	1000	30	1000	3	7000
WS - 18			40			
WS - 19			50			
WS - 20			60			

Table 4. Color Measurements and Light Fastness Results of Samples

	Renk Ölçümü					Işık Haslığı				
	L	a	b	Gloss	Renk Ölçümü	L	a	b	Gloss	ΔE
1	87,79	0,27	11,01	11,38		83,61	3,42	28,38	9,8	18.14
2	88,98	-0,71	11,14	11,39		82,91	3,85	29,69	10,52	20.04
3	88,7	-0,57	11,54	11,03		83,08	3,57	29,3	10,37	19.08
4	84,84	0,48	11,48	11		82,37	3,55	28,94	8,9	17.89
5	89,94	-0,18	12,25	12,67		83,26	4,11	30,08	9,4	19.51
6	90,29	-0,26	12,23	12,55		83,45	3,93	30,09	10,74	19.57
7	89,99	-0,25	12,31	12,74		83,77	3,68	29,55	10,57	18.74
8	90,01	-0,04	12,46	11,71		82,94	3,93	29,78	9,37	19.12
9	89,83	0,47	12,74	10,85		83,98	3,53	27,72	10,6	16.40
10	89,82	0,07	12,86	12,39		83,78	3,58	28,52	11	17.14
11	90,02	-0,58	11,56	11,79		83,26	3,62	28,65	11,4	18.85
12	89,38	-0,49	11,1	11,42		83,44	3,45	28,44	7,07	18.74
13	90,4	-0,21	11,64	12,02		83,38	3,93	29,85	8,82	19.95
14	90,43	-0,22	11,68	12,6		83,74	3,8	29,71	10,22	19.64
15	90,41	-0,11	11,63	12,45		83,2	3,48	26,97	11,52	17.32
16	90,2	-0,01	11,86	12,03		83,23	3,88	29,6	11,37	19.45
17	87,54	-0,03	13,54	12,14		82,57	3,96	30,07	12,39	17.71
18	87,56	-0,03	13,97	11,09		82,41	3,85	29,26	7,42	16.59
19	88,32	-0,02	13,53	11,47		85,52	3,45	29,05	12,89	16.14
20	87,96	0,01	13,11	11,88		83,1	3,74	28,88	8,79	16.91

5-Minute Samples: Distinct temperature-dependent variations in color values were observed in samples subjected to a 5-minute resting period. The WS-1 sample prepared at 30 °C exhibited the lowest brightness, with an L* value of 87.79, while an overall decline in brightness became evident as temperature increased. Notably, the WS-2 sample at 40 °C demonstrated the highest brightness (L* = 88.98) and a pronounced greenish hue (a* = –0.71). These shifts in color coordinates indicate that rising temperature exerts a direct influence on the optical properties of the paper surface.

Lightfastness tests revealed significant color changes in all samples (ΔE = 17.89–20.04). The most pronounced change (ΔE = 20.04) occurred in the WS-2 sample at 40 °C, which also recorded the highest gloss value. Conversely, the WS-4 sample at 60 °C stood out for having both the lowest brightness (L* = 84.84) and the smallest color difference (ΔE = 17.89) within this group.

10-Minute Samples: Samples conditioned for 10 minutes exhibited noticeably higher L* values than those in the 5-minute group. As temperature increased, the b* (yellowness) parameter showed an upward trend, reaching its peak (b* = 12.46) in WS-8 at 60 °C. The a* parameter, which indicates color tone, remained negative across all samples (ranging from –0.26 to –0.04), confirming a dominant greenish hue.

Lightfastness testing revealed clear color alterations (ΔE = 18.74–19.57). The greatest shift (ΔE = 19.57) was recorded for WS-6 at 40 °C, while WS-7 at 50 °C exhibited the smallest change (ΔE = 18.74). An approximate increase of 18 units in b* values suggests a strong tendency toward yellowing under light exposure.

15-Minute Samples: Color characteristics of samples held for 15 minutes differed markedly from previous groups. L* values clustered within 89.38–90.02, reflecting a consistently high brightness profile. The WS-9 sample (30 °C) exhibited an a* value of 0.47, notably higher than the others, indicating a slight reddish tint. Variations in b* values with rising temperature were also evident: 12.74 (30 °C, WS-9), 12.86 (40 °C, WS-10), 11.56 (50 °C, WS-11), and 11.10 (60 °C, WS-12). These results suggest a non-linear relationship between temperature and yellowness.

Lightfastness results showed ΔE values ranging from 16.40 to 18.85, generally lower than those observed in the 5- and 10-minute groups. WS-9 achieved the best performance (ΔE = 16.40), accompanied by a relatively modest increase in b* (27.72). Gloss analysis revealed a striking 38% reduction in WS-12 (from 11.42 to 7.07), indicating that samples held at higher temperatures are more susceptible to surface degradation under light exposure.

30-Minute Samples: Samples conditioned for 30 minutes exhibited the most uniform color profiles compared to shorter durations. L* values remained within a narrow range (90.20–90.43), reflecting exceptional brightness. WS-13 (30 °C) and WS-14 (40 °C) displayed slight greenish tones, with a* values of –0.21 and –0.22, respectively, while the stability of these values across temperatures was noteworthy. b* values ranged between 11.63 and 11.86, implying that extended conditioning

time standardizes the yellowness parameter. Gloss values remained consistent (12.02–12.60), reinforcing the uniformity in surface quality.

Lightfastness tests yielded ΔE values between 17.32 and 19.95. WS-15 (50 °C) recorded the smallest color difference (ΔE = 17.32), along with a relatively low increase in b* (26.97). A positive shift in a* values (average +3.75 units) was particularly evident. Gloss variations ranged from 20% to 30% across this group.

60-Minute Samples: Samples exposed for 60 minutes exhibited a distinct color profile compared to all other groups. L* values dropped to 87.54–88.32, approximately 2–3 units lower than shorter durations, indicating reduced brightness. WS-17 (30 °C) and WS-18 (40 °C) maintained near-neutral tones (a* ≈ –0.03), with only minimal fluctuations at higher temperatures. In contrast, b* values increased significantly (13.11–13.97), reflecting an intensified yellowing effect under prolonged exposure. Gloss measurements (11.09–12.14) suggest that surface quality remained relatively stable despite these changes.

Lightfastness testing produced ΔE values ranging from 16.14 to 17.71. WS-19 (50 °C) demonstrated the lowest color change (ΔE = 16.14), with its post-test L* value rising to 85.52—a noteworthy observation. Increases in b* (29.05–30.07) were comparable to other groups, while changes in a* (+3.45 to +3.96) remained within controlled limits. Gloss reductions of 30–40% were recorded, with WS-18 showing the sharpest decline (from 11.09 to 7.42, approximately 33%), indicating pronounced surface deterioration under these conditions.

Table 5. Measurement of Sample Weight, Surface Smoothness, Air Permeability, and Contact Angle

Sample	Grammage (g/m2)	Surface Smoothness ml/min	Air Permeability µm/pas	Contact Angle 0
WS - 1	89.3	4,053	5,71	
WS - 2	82.2	5,263	8,37	40.2
WS - 3	98.8	5,107	6,55	
WS - 4	60.3	4,705	10,2	
WS - 5	92.3	4,827	8,45	
WS - 6	82.2	4,725	7,08	41.8
WS - 7	86.3	4,299	6,89	
WS - 8	88.8	5,051	6,54	
WS - 9	108.3	6,238	5,35	
WS - 10	75.7	3,887	7,86	40.9
WS - 11	120.7	6,395	4,92	
WS - 12	94.6	6,001	6,15	
WS - 13	79.8	4,502	6,76	
WS - 14	86.3	3,887	6,11	47.0
WS - 15	98.2	5,798	5,89	
WS - 16	117.1	6,919	4,71	
WS - 17	68.1	4,852	13,1	
WS - 18	62.7	3,094	12,3	47.0
WS - 19	123.1	4,461	6,74	
WS - 20	80.1	3,829	10,8	

Based on the data presented in Table 5, the physical properties of recycled cellulose fibers under varying conditioning times and temperatures were comprehensively examined. The findings confirm that processing parameters exert a significant influence on sample grammage, surface smoothness, and air permeability.

The basis weight of the samples exhibited considerable variation, ranging from 60.3 to 123.1 g/m². Within the 5-minute conditioning group, the lowest value was recorded at 60.3 g/m² for the 60 °C sample (WS-4), while the highest value, 98.8 g/m², occurred at 50 °C (WS-3). For the 10-minute group, basis weights ranged between 75.7 and 92.3 g/m², whereas the 15-minute group reached a peak of 108.3 g/m² (WS-9). The 60-minute group, in particular, displayed a remarkably wide distribution, with values spanning from 60.3 to 123.1 g/m².

Surface smoothness measurements clearly reflected the influence of both temperature and resting time on fiber distribution. In the 5-minute group, the best surface smoothness was achieved at 30 °C with 4,053 ml/min (WS-1), increasing to 5,263 ml/min at 40 °C. The maximum value, 6,919 ml/min, was observed in WS-16 after 15 minutes of conditioning. A closer look at surface smoothness trends reveals distinct patterns for samples conditioned at 40 °C. While the 5-minute sample at this temperature (WS-2: 5,263 ml/min) exhibited higher smoothness compared to other temperatures within the same group, prolonged resting times—especially 15 minutes and beyond—resulted in a sharp decline in smoothness for 40 °C samples, reaching as low as 3,094 ml/min (WS-18). These findings underscore the dynamic nature of temperature effects when combined with extended resting periods.

Air permeability measurements ranged from 4.71 to 13.1 µm/pass. In the 5-minute group, the lowest permeability was observed in WS-1 at 30 °C (5.71 µm/pass), while WS-4 at 60 °C recorded the highest value (10.2 µm/pass). For samples conditioned for 10 and 30 minutes, an inverse relationship emerged between temperature and air permeability, with higher temperatures corresponding to reduced permeability. Particularly striking was the 15-minute group, where extremely low permeability values were recorded, such as 4.92 µm/pass for WS-11.

Contact angle measurements provided critical insights into the hydrophobic character of the samples, with values ranging from 40.2° to 47.0°. The highest contact angles (47.0°) were measured in WS-14 (40 °C, 30 minutes) and WS-18 (40 °C, 60 minutes), suggesting a pronounced surface hydrophobicity under these conditions.

The data presented in Figure 2 systematically illustrate basis weight variations across samples prepared under

different resting times and temperatures. The X-axis represents the sample codes (WS-1 to WS-20), while the Y-axis denotes basis weight within the 60–120 g/m² range. The analysis clearly demonstrates that processing parameters exert a significant influence on the basis weight distribution of the samples.

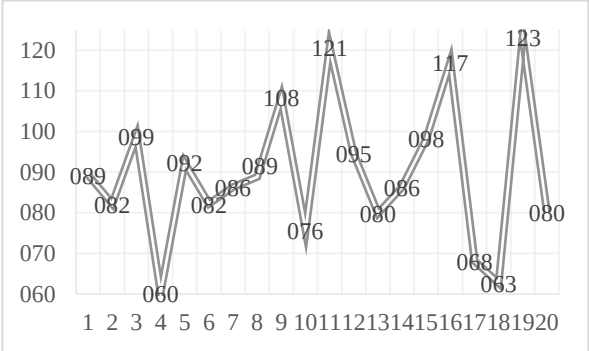

Figure 2. Basis Weight Measurements of the Samples

The weight distribution graph in Figure 2 shows that the samples exhibit values ranging from 60 to 123 g/m². The lowest values, around 60 g/m², were recorded for WS-4, while the highest exceeded 123 g/m², as observed in WS-11 and WS-19. A general upward trend is evident with increasing resting time: 5-minute samples cluster within 60–100 g/m², whereas those conditioned for 15 minutes fall between 90 and 120 g/m². In the 60-minute group, however, values vary widely, including both very low (~62 g/m²) and very high (~123 g/m²) measurements. Temperature influence is particularly pronounced at 40 °C, where samples consistently occupy the lower range of the graph (lower basis weights), while those at 50 °C exhibit relatively higher values. At 60 °C, the presence of extreme outliers is notable. This visual analysis suggests that a 15-minute resting period yields comparatively stable basis weights, whereas prolonged conditioning (60 minutes) introduces inconsistency.

Surface characteristics of the samples reveal a distinct dependency on time, as evidenced by Figure 3, which presents surface smoothness and air permeability measurements for specimens conditioned at 30 °C under varying durations.

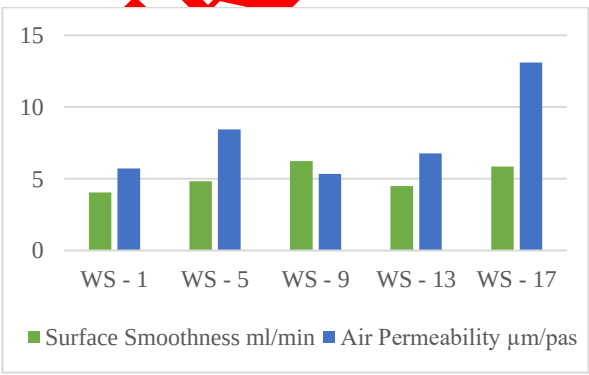

Figure 3. Surface Smoothness and Air Permeability of Samples at 30 °C with Different Resting Times

The graph indicates that surface smoothness values start at approximately 4,053 ml/min during the 5-minute interval, rise to an optimal 6,238 ml/min at 15 minutes, and then decline to 4,852 ml/min after 60 minutes of conditioning. Air permeability, in contrast, exhibits an opposing trend: the lowest readings (5.35 µm/pass) occur at 15 minutes, while the highest (13.1 µm/pass) appear in the 60-minute group. These results highlight that a 15-minute resting time achieves an optimal balance—enhancing surface smoothness while reducing air permeability—whereas excessive durations negate these benefits. At a constant temperature of 30 °C, surface properties thus display a non-linear relationship with resting time.

Data presented in Figure 4 further elucidate these dynamics for samples processed at 40 °C under varying resting durations.

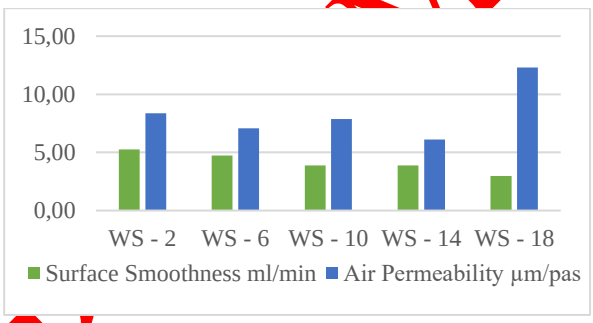

Figure 4. Surface Smoothness and Air Permeability of Samples at 40 °C with Different Resting Times

The graph reveals a clear inverse correlation between surface smoothness and air permeability. From WS-2 (5 minutes) to WS-18 (60 minutes), smoothness values exhibit a continuous decline, falling from approximately 5.2 m³/min initially to about 3.0 m³/min after 60 minutes. Conversely, air permeability rises progressively throughout the same period, reaching approximately 12.3 µm/pass in WS-18. These findings indicate that prolonged resting at 40 °C deteriorates surface quality while rendering the material more permeable. Noticeable deterioration in both parameters begins after 15 minutes, suggesting that at this temperature, the optimal processing time should not exceed 10–15 minutes.

Figure 5 provides additional evidence on surface property variations for samples subjected to different resting durations at a constant temperature of 50 °C.

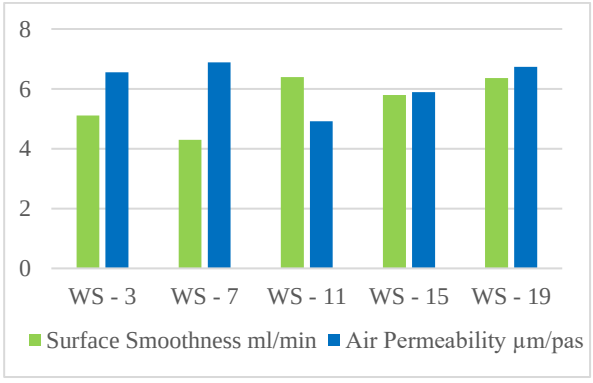

Figure 5. Surface Smoothness and Air Permeability of Samples at 50 °C with Different Resting Times

The graph reveals a fluctuating trend in surface smoothness from WS-3 to WS-19. The highest smoothness is recorded in WS-11 after 15 minutes of conditioning, followed by a noticeable decline in the 60-minute sample (WS-19). Air permeability displays the opposite pattern: the lowest value occurs in WS-11 (15 minutes), whereas the 60-minute sample reaches approximately 6.7 µm/pass. These findings indicate that a 15-minute resting time at 50 °C provides optimal surface smoothness while minimizing air permeability. Even after 60 minutes, surface degradation remains less severe compared to samples processed at 40 °C, suggesting that 50 °C may represent an optimal temperature for achieving balanced physical properties in cellulose fibers.

Data presented in Figure 6 highlight pronounced changes in surface properties under higher thermal exposure, specifically at 60 °C for varying durations.

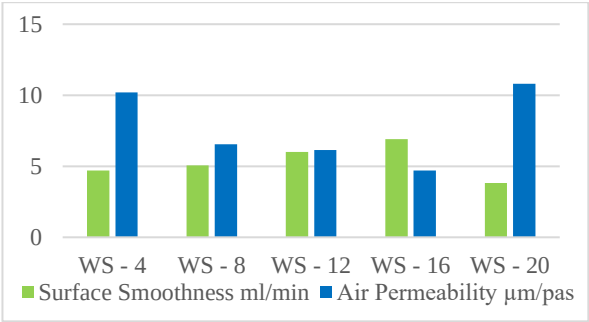

Figure 6. Surface Smoothness and Air Permeability of Samples at 60 °C with Different Resting Times

The graph demonstrates an irregular pattern in surface smoothness across the series, from WS-4 (5 minutes) to WS-20 (60 minutes). While WS-12 (15 minutes) exhibits a comparatively higher smoothness, this value declines substantially by the 60-minute mark. Air permeability, in contrast, shows a clear upward trend with prolonged exposure. These results confirm that extended resting at 60 °C significantly compromises surface quality and increases material porosity. Moreover, even at the 15-minute interval, surface smoothness remains lower than that of equivalent samples conditioned at 30 °C or 50 °C, suggesting that 60 °C constitutes a threshold temperature with detrimental effects on surface integrity.

Figure 7 presents contact angle measurements illustrating changes in surface hydrophobicity for samples maintained at 40 °C across different resting periods.

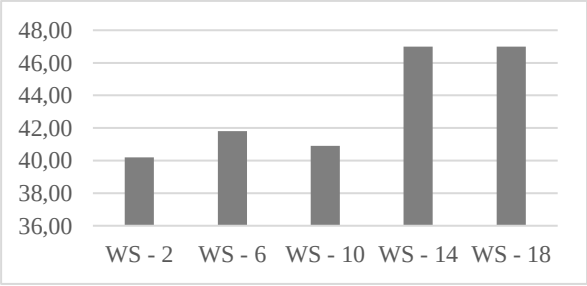

Figure 7. Contact Angle Measurements of Samples at 40 °C with Different Resting Times

The graph shows contact angle values ranging from 40.2° (WS-2, 5 minutes) to 47.0° (WS-18, 60 minutes), with a consistent upward trend as resting time increases. Notably, samples conditioned for 30 and 60 minutes (WS-14 and WS-18) reach the highest angles at 47.0°, indicating a marked enhancement in hydrophobic character. This increase inversely correlates with surface smoothness, suggesting that greater surface roughness promotes water repellency. These observations imply that controlled extension of resting time at 40 °C can improve the hydrophobic performance of cellulose fibers.

4. RESULTS

This study comprehensively examined the structural and optical properties of papers produced from recycled industrial waste under varying disintegration times (5–60 minutes) and temperature conditions (30–60 °C). Experimental findings clearly demonstrated the significant influence of processing parameters on paper quality.

The best overall performance was achieved by sample WS-14, processed for 30 minutes at 40 °C. This sample exhibited high brightness (L* = 90.43), low porosity as indicated by an air permeability of 6.11 µm/pass, and a uniform surface with a smoothness value of 3,887 ml/min. These results suggest that a 30-minute disintegration period helps preserve fiber integrity, while 40 °C provides optimal fiber dispersion.

In terms of color stability, samples held for 30 minutes exhibited lower ΔE values (17.32–19.95) compared to the other groups. Notably, the color shifts observed in these samples after lightfastness testing remained within acceptable limits. In contrast, the 60-minute treatment resulted in a decline in L* values to the range of 87.54–88.32, accompanied by an increase in ΔE, indicating that prolonged processing adversely affects optical properties.

Samples subjected to the 60-minute treatment also showed a pronounced rise in surface roughness and a significant increase in air permeability. For instance, the WS-18 sample demonstrated a 33% reduction in gloss and an air permeability of 12.3 µm/pas. These findings suggest that excessive disintegration times lead to structural degradation of fibers, ultimately reducing paper quality. This outcome reinforces the critical influence of temperature and duration parameters on fiber morphology. Similarly, previous research [11] has reported that variations in temperature and time during sublimation printing play a decisive role in print quality on textile surfaces. Studies involving natural dyes have also documented the direct impact of temperature on color stability [13]. Furthermore, investigations employing pigments derived from microorganisms emphasize that surface properties are highly sensitive to temperature and time variables [13].

The findings confirm the critical role of processing parameters in the recycling of industrial waste paper. Among the tested conditions, the combination of a 30-minute disintegration period and a temperature of 40 °C yielded the most favorable results. These observations are consistent with previous reports in the literature, where recycled fibers have demonstrated optimal performance at disintegration times ranging between 35 and 45 minutes [21].

This study, however, is not without limitations. The potential influence of varying fiber blends and chemical additives was not explored, and the applicability of these laboratory-scale outcomes to full-scale industrial production remains to be verified.

Future research should investigate the influence of alternative fiber sources and surface modification techniques on the properties of recycled papers. Moreover, validating optimization strategies at an industrial scale would significantly enhance the practical relevance of the findings. This study serves as an important reference for optimizing recycling parameters aimed at sustainable paper production.

DECLARATION OF ETHICAL STANDARDS

The author of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Cengiz ŞAHİN: Determining the research issue, planning, conducting the experiments, analyzing the results and writing the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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