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Effects of Microwave Irradiation on the Color and Turbidity of Wastewater from Paper Recycling

Kağıt Geri Dönüşümünden Elde Edilen Atık Suyun Renk ve Bulanıklık Özelliklerine Mikrodalga Işınlamasının Etkileri

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Abstract

This study aims to determine the general optical properties of wastewater generated during the paper recycling process and to investigate the effects of microwave (MW) irradiation on color properties and turbidity removal. The lowest turbidity values were achieved at the highest MW power (360 W) and the longest irradiation time (60 seconds), that more effective results observed when combined with high-speed centrifugation (4000 rpm). The highest turbidity removal efficiency was achieved in sample YD6, with a reduction of 20.3 NTU, confirming that MW irradiation enhanced the separation of suspended solids when used in conjunction with centrifugation. It was revealed that increasing the centrifugation speed enhanced the turbidity removal efficiency. However, color analysis clearly demonstrated that MW irradiation altered brightness (L*), redness-greenness (a*), and yellowness-blueness (b*) color coordinates to a certain extent. The highest total color difference values were recorded in samples XD1 (ΔE: 4.60) and YC2 (ΔE: 5.02), indicating that MW treatment induced significant changes in the color composition of wastewater. Moreover, Hue angle (h^0) analysis further demonstrated the shift in color composition after MW irradiation and centrifugation, reinforcing the potential of this approach for improving wastewater optical quality. It is notable that when the MW power increases, some optical variations occur in color properties of wastewater samples. The findings of this study may suggest that MW irradiation has potential impact, as a pre-treatment method for wastewater treatment in industrial processes such as paper recycling.

Keywords: Paper recycling, wastewater, microwave irradiation, optical properties, turbidity

Özet

Bu çalışmanın amacı, kağıt geri dönüşüm prosesi sırasında oluşan atık suyun genel optik özelliklerini belirlemek ve mikrodalga (MW) ışınlamanın renk özellikleri ve bulanıklık giderimi üzerindeki etkilerini araştırmaktır. En düşük bulanıklık değerleri en yüksek MW gücünde (360 W) ve en uzun ışınlama süresinde (60 saniye) elde edilmiş, yüksek hızlı santrifüjleme (4000 rpm) ile birleştirildiğinde daha etkili sonuçlar gözlemlenmiştir. En yüksek bulanıklık giderme verimliliği 20,3 NTU'luk bir azalma ile YD6 numunesinde elde edilmiş ve MW ışınlamasının santrifüjleme ile birlikte kullanıldığında askıda katı maddelerin ayrışmasını arttırdığını doğrulamıştır. Santrifüj hızının arttırılmasının bulanıklık giderme verimliliğini arttırdığı ortaya çıkmıştır. Bununla birlikte, renk analizi MW ışınlamasının parlaklık (L*), kırmızılık-yeşillik (a*) ve sarılık-mavilik (b*) renk koordinatlarını belli bir düzeyde değiştirdiğini açıkça göstermiştir. En yüksek toplam renk farkı değerleri XD1 (ΔE: 4.60) ve YC2 (ΔE: 5.02) numunelerinde kaydedilmiştir, bu da MW işleminin atık suyun renk bileşiminde önemli değişikliklere neden olduğunu göstermektedir. Ayrıca, Hue açısı (h^0) analizi, MW ışınlama ve santrifüjlemeden sonra renk bileşimindeki değişimi daha da göstererek bu yaklaşımın atık su optik kalitesini iyileştirme potansiyelini güçlendirmiştir. MW gücü arttığında, atık su numunelerinin renk özelliklerinde bazı optik değişimlerin meydana gelmesi dikkat çekicidir. Bu çalışmanın bulguları, kağıt geri dönüşümü gibi endüstriyel süreçlerde atık su arıtımı için bir ön arıtma yöntemi olarak MW ışınlamanın potansiyel bir etkiye sahip olduğunu gösterebilir.

Anahtar Kelimeler: Kağıt geri dönüşümü, atık su, mikrodalga ışınlama, optik özellikler, bulanıklık

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1. Introduction

The depletion of natural resources has led to a growing interest in paper recycling as an environmentally sustainable practice worldwide (Čabalová et al., 2011; Sahin, 2013). This process plays a crucial role in the paper industry by enabling the conversion of recovered paper into new products. However, the production of high-quality paper, particularly for printing and writing applications, often requires virgin pulp (Biermann, 1996). The recycling process consists of multiple stages, including repulping, screening, deinking, and papermaking. The repulping process involves dispersing waste paper in water to separate fibrous and non-fibrous materials, while the screening removes large fibrous and non-fibrous contaminants such as staples and metallic impurities. Moreover, deinking (via washing or flotation methods) is a important step in paper recycling and is essential for the removal of ink particles, particularly those smaller than 25 µm (Borchardt et al., 1998; Zhenying et al., 2009; Kamali and Khodaparast, 2015).

Despite its environmental benefits, paper recycling introduces various pollutants into wastewater, including chemical additives and by-products used or formed during the recycling process, such as hydrogen peroxide, chlorinated bleaching agents, starch residues, calcium ions (Ca^{2+}), synthetic adhesives, and sulfate compounds. Since these contaminants pose significant environmental threats, it is crucial to identify effective treatment methods and and develop effective water treatment and management strategies tailored for the paper recycling industry (Pokhrel and Viraghavan, 2004; Toczyłowska-Mamińska, 2017; Han et al., 2021; Coskun, 2022). Therefore, wastewater treatment in the pulp and paper industry is particularly challenging and costly, necessitating multi-stage approaches that include primary, secondary, and tertiary treatment processes (Hubbe et al., 2016; Han et al., 2021). Effective wastewater treatment is critical for ensuring ecological sustainability. Over the years, various physical, chemical, and biological methods have been developed to address this issue. Commonly used techniques include sedimentation and flotation, coagulation and precipitation, filtration, reverse osmosis, adsorption, oxidation and ozonation, as well as biological and physicochemical treatment methods (Annadurai et al., 2002; Huang and Logan, 2008; Kamali and Khodaparast, 2015). A typical microwave system consists of an applicator, which directs microwaves to the target area, and a generator, which is known as a magnetron. Microwaves are emitted as controlled beams and absorbed by surrounding materials, facilitating energy transfer (Özkan and Şahin, 2023; Kardeş et al., 2024). MW systems stand out as an innovative solution based on the principles of electromagnetic wave interactions within the microwave spectrum (Clark and Sutton, 1996). Specifically designed MW systems enable the transfer of high energy to molecules, generating substantial thermal energy within a short period. This energy can either completely disrupt structural components or enhance molecular mobility to a limited extent, leading to heat generation through friction (Appleton et al., 2005). MW radiation possesses higher energy levels compared to ultraviolet (UV) and infrared radiation, allowing it to break molecular bonds and influence chemical interactions through electromagnetic energy.

In this study, microwave technology was employed as a pre-treatment method for the removal of wastewater, generated during the paper recycling process. Following microwave irradiation, a centrifugation process was applied to enhance the removal of color and turbidity from the wastewater. The results obtained at various microwave power levels and exposure times were compared to evaluate their effectiveness.

2. Material and Method

The wastewater used in this study was obtained from a laboratory-scale newspaper recycling process. Newspaper sheets were cut into small pieces (1–5 cm) and pre-soaked for 24 hours at 20 °C under 65% relative humidity. The humidity level was maintained using a controlled-environment chamber to ensure consistent soaking conditions. A 1:5 weight/volume ratio (1000 g newspaper to 5000 ml water) was used during soaking. After complete wetting, the secondary pulp was prepared using a laboratory pulper. The resulting wastewater was separated by filtering through a 200-mesh sieve, which was chosen to effectively remove residual fiber fragments and solid impurities while allowing dissolved and fine particulate matter to pass through for further analysis (Özkan, 2023).

For treatment, wastewater samples (120 ml each) were subjected to microwave irradiation in a 500 ml glass beaker, placed at the center of a household microwave oven. MW treatment was applied at four power levels (90, 180, 270 and 360 W) for six durations (10-60 seconds, in 10-second intervals). Following MW treatment, samples were centrifuged using a YUDO-800D centrifuge at either 1000 rpm (low speed) or 4000 rpm (high speed) for three minutes. The study included 51 groups: one untreated raw wastewater sample (labeled as C, representing the control without any centrifugation or MW exposure), two centrifuged control samples (XC0 and YC0) representing samples centrifuged at 1000 rpm and 4000 rpm without MW treatment, and 48 MW-treated samples (A1–A6 for 90 W, B1–

B6 for 180 W, C1–C6 for 270 W, and D1–D6 for 360 W). The experimental design is summarized in Table 1.

Table 1. Experimental Design.

	X (1000 RPM)		Y (4000 RPM)	
Samples	**MW (W)**	**Time (second)**	**MW (W)**	**Time (second)**
C	-	-	-	-
C0	-	180	-	180
A1	90	10	90	10
A2	90	20	90	20
A3	90	30	90	30
A4	90	40	90	40
A5	90	50	90	50
A6	90	60	90	60
B1	180	10	180	10
B2	180	20	180	20
B3	180	30	180	30
B4	180	40	180	40
B5	180	50	180	50
B6	180	60	180	60
C1	270	10	270	10
C2	270	20	270	20
C3	270	30	270	30
C4	270	40	270	40
C5	270	50	270	50
C6	270	60	270	60
D1	360	10	360	10
D2	360	20	360	20
D3	360	30	360	30
D4	360	40	360	40
D5	360	50	360	50
D6	360	60	360	60

2.1. Color and Turbidity Measurements

The brightness/darkness (L*), redness/greenness (a*), yellowness/blueness (b*), and total color difference (ΔE) values of the water samples were measured according to the CIE Lab* 1976 (Commission Internationale d'Eclairage) standard. The measurements were performed automatically using an X-Rite 962 (Grand Rapids, Michigan) spectrophotometer under a 2° observer angle and 6500 Kelvin daylight (D65) standard illumination. The liquid samples were placed in optically clear glass cells with a fixed path length of 10 mm, ensuring a consistent sample thickness during measurement. All measurements were conducted at room temperature, and the instrument was calibrated with a standard white tile before use. The turbidity properties of MW-treated samples and control samples subjected to two different centrifugation parameters (X and Y) were evaluated in accordance with the ISO 7027 standard. For each sample group, six measurements were taken using a Hanna HI 93703 turbidity meter (Woonsocket, USA). Light microscopy at 10x magnification was used to observe sample appearance. The general visual and light microscopic (x10) appearance of samples were made in laboratory conditions.

3. Results and Discussion

3.1. General and Microscopic Evaluation of Samples

Figure 1 shows the general appearance of raw contaminated water (C), control samples with only centrifugation at two different levels (XC0 and YC0) and water samples (XD6 and YD6) subjected to MW irradiation at 360 W for 60 seconds. As observed here, it is understood that the colour of the water samples lightened to a certain extent with MW treatment.

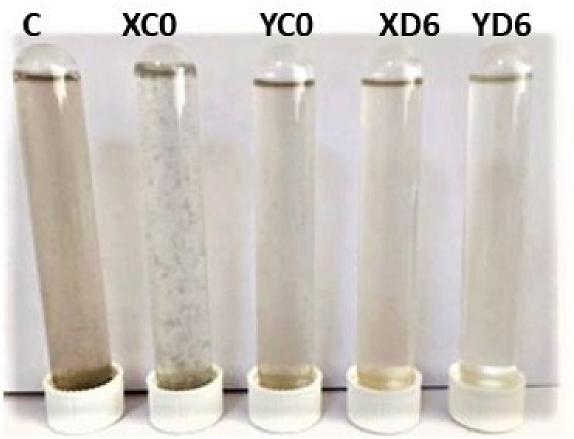

Figure 1. General view of the samples.

To better observe the effects of MW radiation and subsequent centrifugation, samples were examined under light microscopy (10x magnification), and the results are shown in Figure 2. Compared to the control samples (C and XC0 and YC0), it is seen that centrifugation has an effect on the aggregation (XC0) and removal (YC0) of colloidal substances in the water, while MW application (XD6/YD6) has a significant effect on the color of the water and the removal of suspended substances.

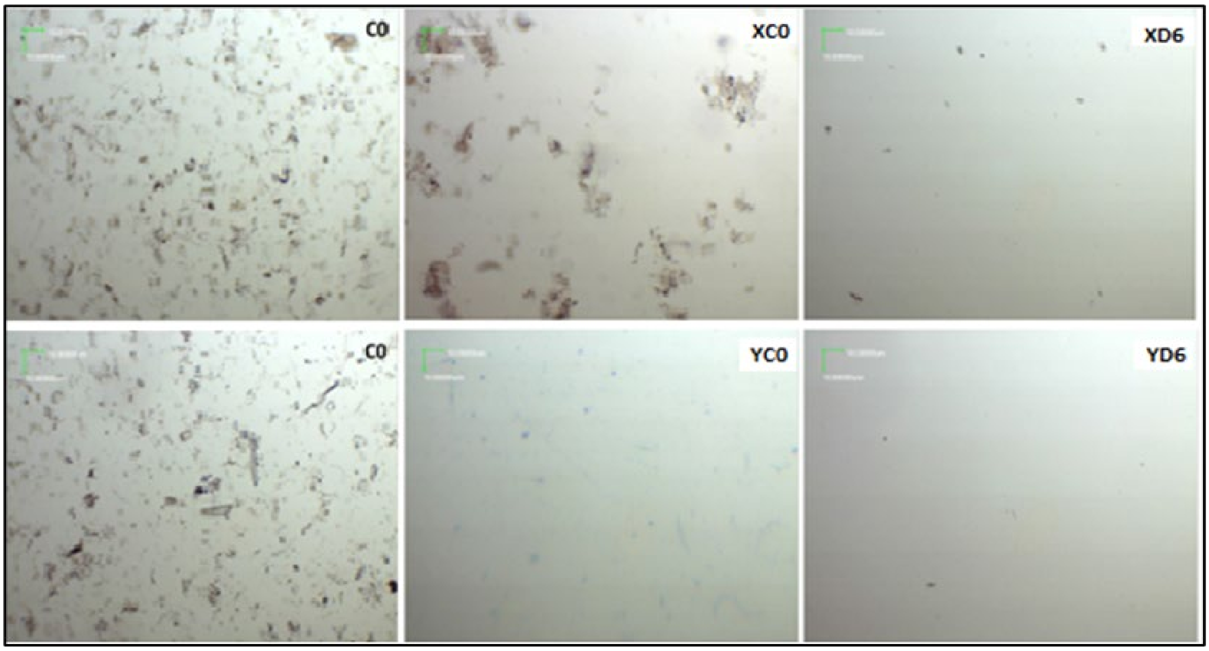

Figure 2. View of the samples under light microscopy at 10x magnification.

3.2. Turbidity Properties of Samples

The comparative turbidity values of the samples subjected to two different centrifuge speed levels and subsequent MW treatment are shown in Table 2. The turbidity value of the raw control water sample without any removal process was measured as 161 NTU. However, in low speed centrifugation (X), the turbidity value decreased to 53.5 NTU. MW treatment appeared to significant reductions in the turbidity values of the water samples. Moreover, the turbidity values of the samples decreased continuously in accordance with MW time and power.

In the samples centrifuged at low speed, the lowest turbidity value of 28.7 NTU was observed in the test sample of XD6 at 360 W and 60 seconds. This value indicates that the turbidity decreased approximately -12.5 NTU compared to the control sample (XC0: 53.5 NTU). However, the turbidity value of the control sample centrifuged at high speed was measured as 37.3 NTU. The similar trend found in the other low speed centrifuged sample was also observed in the high speed and MW trials. The lowest turbidity value of 17.0 NTU or the highest turbidity removal (-20.3 NTU) was observed in the 360 W and 60 seconds with sample of YD6.

Table 2. Effect of MW application on turbidity characteristics.

	X		Y	
Samples	**T (NTU)**	**ΔT (NTU, XC0 from)**	**T (NTU)**	**ΔT (NTU, YC0 from)**
Controls				
C	161	-	161	-
C0	53.5	-107.5	37.3	-123.7
90 W				
A1	41.0	-12.5	24.8	-12.5
A2	37.8	-15.7	24.3	-13,0
A3	36.7	-16.8	23.5	-13.8
A4	34.7	-18.8	22.8	-14.5
A5	33.2	-20.3	21.2	-16.1
A6	31.7	-21.8	20.8	-16.5
180 W				
B1	37.7	-3.3	24.5	-12.8
B2	36.3	-4.7	23.7	-13.6
B3	35.7	-5.3	22.0	-15.3
B4	33.8	-7.2	20.7	-16.6
B5	32.7	-8.3	20.0	-17.3
B6	31.2	-9.8	19.7	-17.6
270 W				
C1	36.7	-4.3	23.3	-14,0
C2	35.8	-5.2	22.8	-14.5
C3	34.3	-6.7	20.7	-16.6
C4	32.2	-8.8	19.5	-17.8
C5	30.3	-10.7	18.8	-18.5
C6	29.2	-11.8	18.3	-19
360 W				
D1	33.8	-7.2	21.5	-15.8
D2	33.3	-7.7	20.5	-16.8
D3	32.5	-8.5	18.8	-18.5
D4	30.8	-10.2	18.0	-19.3
D5	29.2	-11.8	17.5	-19.8
D6	28.5	-12.5	17.0	-20.3

Since the turbidity characteristic of the water source has significant effects on the quality of the water, the effectiveness of the water treatment/disposal process compared to the control is important for the success of the selected method. In Figure 3, the turbidity removal rate (%) of the MW treated samples compared to the control sample is given comparatively for both centrifugation cycles. When the graphs are analyzed, it is clearly seen that MW treatments have a positive effect on the reduction of turbidity properties of the samples after both centrifugation cycles, and that higher speed (Y) is more effective in reducing turbidity than lower speed (X). The highest turbidity removal rate (%) in both centrifuge groups was observed in XD6 and YD6 samples with the highest MW power (360 W) and the longest time (60 seconds), 46.73% and 54.42%, respectively.

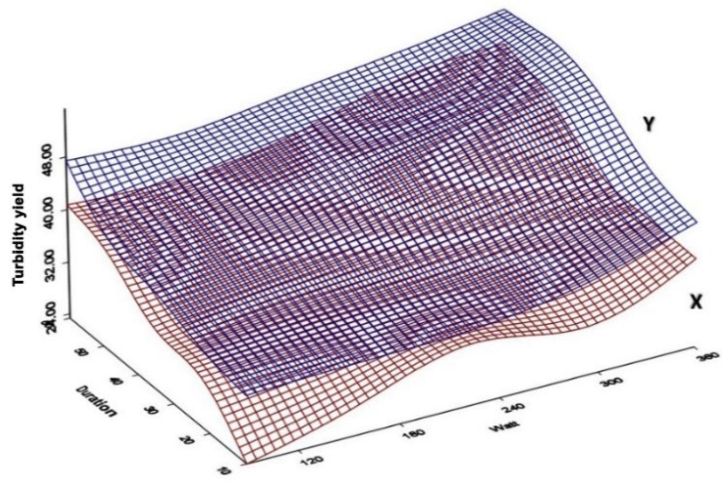

Figure 3. Effect of MW time and power on the turbidity yield.

3.2. Color Characteristics of Samples

In many standards and experimental applications, it is generally recommended to measure the color (true color) of turbidity of water after centrifugation and filtration (with using 0.45 mm filter paper) (Cırık et al., 2013; Sawyer et al., 2020). In the color measurement of wastewater samples after MW process was used and color values were determined. In Table 3, according to CIE L*a*b* (1976) standard, the true color values of the post MW irradiated wastewater generated from waste paper recycling under similar conditions after two different centrifugation applications are shown comparatively. For L* properties, all centrifuged and MW treated samples shown lower L* values than the control samples (L*= 9.83 (XC0); L*= 10.45 (YC0)). However, the lowest L* value of 5.42 and 5.99 were found with samples XD6 and YD6 with the highest MW power and time treatment at both centrifuge speeds, respectively.

When the a* of the water were examined, both green (-a) and red (+a) color values were determined in the samples centrifuged at low speed. The lowest red value of 0.03 was found in sample of XD6 and the highest greenness value of -0.61 was found in sample of XA4. The highest redness value a*: 0.40 was calculated in YC3 sample and the highest greenness value a: -0.34 was calculated in YD6 sample. However, it should be noted that most a* and b* values remained within the low range (between approximately -0.6 and +0.6), which is close to the repeatability threshold of the spectrophotometer (±0.2 to ±0.3, depending on sample clarity). Therefore, slight shifts between positive and negative values, such as those seen in samples a* may partly result from the inherent variability of the instrument, particularly for transparent or low-colored liquid samples. Additionally, such fluctuations can be influenced by minor changes in suspended particle content, light scattering, or slight differences in the optical path during measurement. For b* properties, a more complicated results were observed. The highest yellow color value of b*: 0.81 found in YB6 sample and the highest blue color b*: -2.16 was observed in YD3 sample. Similar trend was also observed in the samples subjected to high speed centrifugation after MW application. However, the samples showed more blue (-b*) color properties at high power level (360 W). The highest blueness value of b*:-2.20 found with sample YC4. It is notable that the 360 W MW power conditions impact more blue (-b) color while lower MW power applied samples show more yellow (+b) color characteristics, in all durations. The changes in the obtained findings are thought to be related to the formation or breakdown of chromophoric compounds during microwave irradiation. The high energy input may affect the light absorption in the blue region by altering the organic structures in the wastewater.

Table 3. Effect of MW application on color characteristics (CIE L*a*b*).

Samples	X			Y		
	L*	a*	b*	L*	a*	b*
			Controls			
C	9.91	0.54	-2.12	9.91	0.54	-2.12
C0	9.83	0.13	-1.70	10.45	-0.50	1.07
			90 W			
A1	8.59	-0.38	0.48	8.91	0.29	-2.01
A2	7.54	-0.23	0.24	8.03	-0.28	-2.08
A3	7.81	-0.25	0.41	9.25	0.28	-1.86
A4	8.09	-0.61	0.75	8.98	0.17	-2.08
A5	7.16	-0.12	0.10	8.84	-0.08	-2.10
A6	7.27	-0.03	0.21	9.37	0.19	-2.08
			180 W			
B1	8.23	-0.47	0.60	8.59	0.35	-2.19
B2	8.09	-0.45	0.60	7.80	0.39	-2.25
B3	6.04	-0.19	0.10	9.22	0.30	-1.78
B4	7.31	-0.17	0.15	8.10	0.23	-1.71
B5	7.75	-0.49	0.79	6.48	-0.01	-1.73
B6	6.98	-0.36	0.81	7.74	-0.09	-1.26
			270 W			
C1	8.17	-0.39	1.11	7.78	0.37	-1.84
C2	5.53	-0.13	0.15	8.07	0.18	-1.71
C3	6.28	-0.23	0.20	8.94	0.40	-1.82
C4	5.76	-0.26	0.23	7.53	0.18	-2.20
C5	8.80	-0.35	0.24	8.58	0.45	-2.03
C6	6.11	-0.28	0.07	7.32	0.11	-1.77
			360 W			
D1	6.82	0.34	-2.0	6.0	-0.29	0.20
D2	6.14	0.14	-1.73	8.44	-0.22	0.87
D3	6.36	0.2	-2.16	6.27	-0.16	0.34
D4	6.78	0.34	-2.13	6.25	-0.39	0.42
D5	6.54	0.10	-1.83	6.38	-0.20	0.50
D6	5.42	0.03	-1.68	5.99	-0.34	0.23

In order to find the correlation between color coordinate properties and MW irradiation parameters (durations and power levels), the obtained color values presented in Table 3 were used to create Figure 4 for L* coordinate, Figure 5 for a* coordinate and Figure 6 for b* coordinate, respectively. The coefficient of determination (R^2) values were calculated using linear regression analysis based on the least squares method. For L* properties a coefficient value of $R^2 = 0.6978$ was obtained for low speed centrifugation, while $R^2 = 0.4841$ was found for high speed centrifugation. This indicates a lower correlation between brightness and MW parameters at higher centrifugation speeds. These results may suggest that MW effects on color properties are more pronounced under low-speed centrifugation conditions.

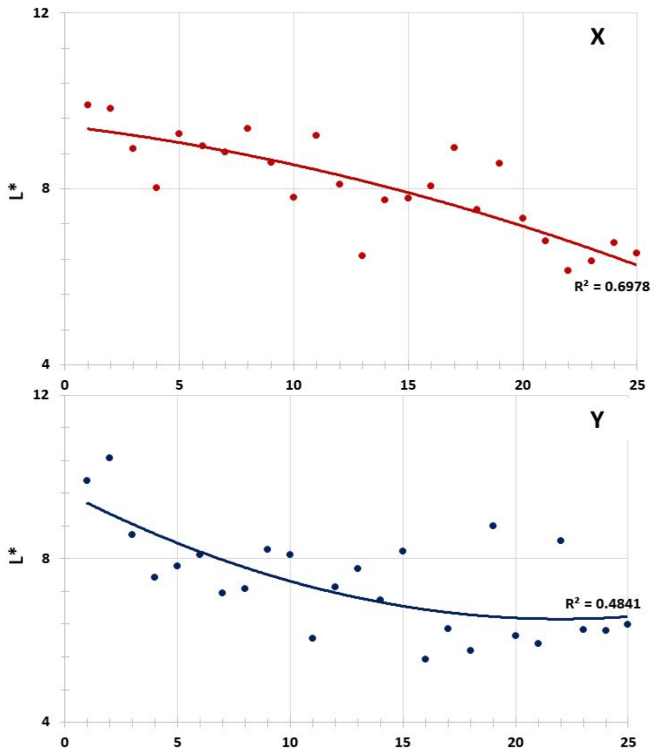

Figure 4. Effect of MW power and duration on L* coordinate of wastewater samples.

Figure 5 shows the relationship between the measured a* values of MW-irradiated samples under two different centrifugation conditions. A simple linear regression model was used to evaluate the correlation between a* values and MW parameters (power and duration). However, the results showed very low coefficients of determination ($R^2 = 0.0015$ for low-speed and $R^2 = 0.0835$ for high-speed centrifuged samples), indicating that the a* values vary almost independently of MW power and exposure time. These findings suggest that microwave irradiation, under the tested conditions, does not produce a consistent or predictable change in the chromaticity of the effluent with respect to the red-green color axis.

This is also visually confirmed in Figures 6 and 7, where no meaningful trend or directional change is observed in a* and b* values as MW power increases.

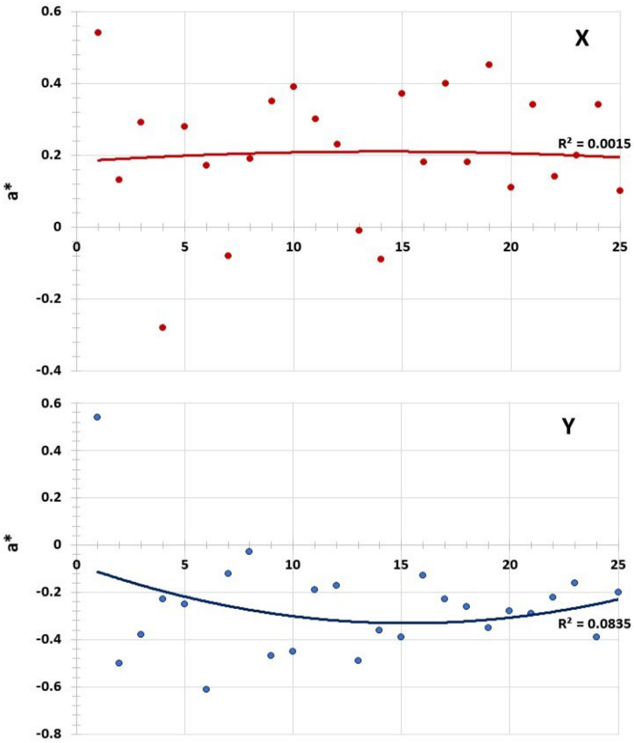

Figure 5. Effect of MW irradiation on a* color coordinate.

Figure 6 shows the relationships between the measured b* (yellowness-blueness) numerical values of the water samples. The similar situation for b* color properties encountered as presented for a* color coordinate that the relationship between the measured b* values of both types of water samples was found to be very low and theoretically uncorrelated (R^2: 0.0528 for low centrifuged samples and R^2: 0.1304 for high centrifuged samples).

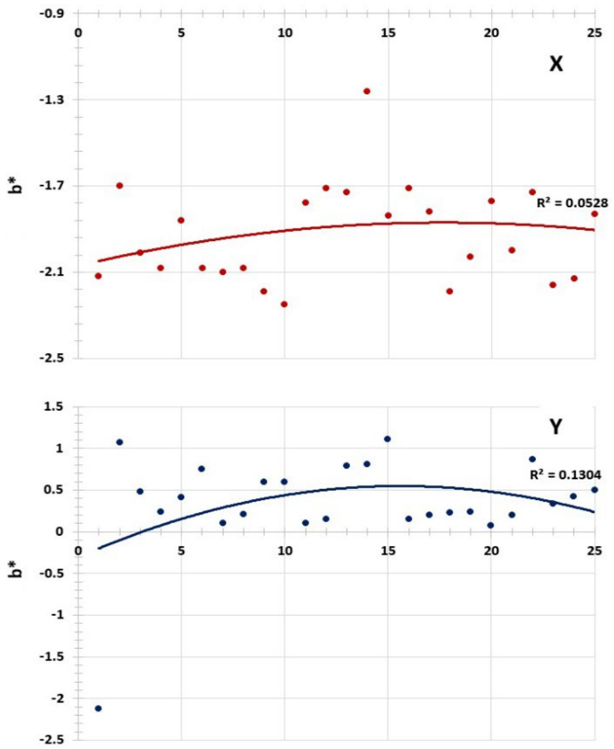

Figure 6. Effect of MW irradiation on b* color coordinate.

The hue angle (h^0) of the samples was determined from the findings. The h^0 value refers to the determination of the basic color families of the measured object, such as red, blue and green. In that case, the position of the measured value in colour space (hue angle) can be used to describe the color of many objects (Hach-Lange, 2023). The Hue values obtained during the measurement of the true color properties of the samples are marked on the color sphere (Figure 7). It was found that there was only a 20 degrees difference (between 2620 and 2820) between the Hue values of the samples subjected to MW and then centrifuged at low speed (XC0h: 2740). In the color sphere, these angle values were observed to be between blue (-b) and red (+a). The difference between the Hue values of the samples subjected to MW and then centrifuged at higher speed was found to be quite large and ranged from 110 and 1450 (YC0h: 1150). When these values were placed on the color sphere, it was determined that the color of the high speed and MW treated water was marked to be between yellow (+b) and green (-a).

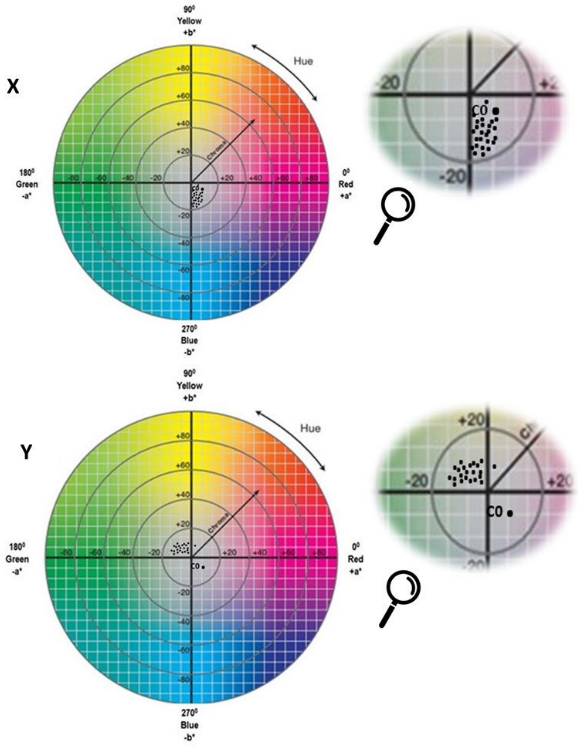

Figure 7. Color sphere representation of gloss Hue values of samples.

The color values were evaluated using the total color difference metric (ΔE*), which indicates the perceptual difference between two colors in the CIE Lab* color space. In this study, ΔE* values were calculated using the Equation 1:

$$\Delta E_{ab} = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2} \quad (1)$$

L* represents the level of brightness or darkness, ranging from 0 to 100, where lower values indicate darker shades (0 being black and 100 representing pure white). The a* value signifies the position on the red-green axis, with positive values (a+) indicating redness and negative values (a-) indicating greenness. Similarly, the b* value corresponds to the yellow-blue axis, where positive values (b+) denote yellowness and negative values (b-) indicate blueness. The total color difference (ΔE) is a combined measure of variations in all these parameters. This metric expresses the color difference, not the direct removal of specific contaminants, although a significant ΔE* may imply changes in chromophoric compounds affected by treatment. The calculated ΔE* values for all treated samples are presented in Table 4. Among the low-speed centrifuged samples, the highest ΔE* was 4.60 (XD1), treated with 360 W microwave power for 10 seconds. In the high-speed centrifuged group, the highest ΔE* was 5.02 (YC2), treated with 270 W for 20 seconds. These results suggest that microwave irradiation followed by centrifugation induces a perceptible color shift in the treated wastewater compared to the untreated control sample.

Table 4. Total color difference (ΔE) values of the samples.

Samples	ΔE (X)	ΔE (Y)
C0	0	0
	90 W	
A1	0.98	1.96
A2	1.88	3.04
A3	0.62	2.73
A4	0.93	2.38
A5	1.09	3.45
A6	0.60	3.33
	180 W	
B1	1.35	2.27
B2	2.12	2.41
B3	0.64	4.53
B4	1.73	3.29
B5	3.35	2.71
B6	2.15	3.48
	270 W	
C1	2.07	2.28
C2	1.76	5.02
C3	0.94	4.27
C4	2.35	4.77
C5	1.33	1.85
C6	2.51	4.46
	360 W	
D1	4.60	3.03
D2	2.04	3.69
D3	4.26	3.50
D4	4.25	3.09
D5	4.12	3.29
D6	4.54	4.41

Figure 8 shows ΔE* of water samples centrifuged at two different speeds according to the MW parameter. As can be seen, the color characteristics of the water generally show a similar trend under the same test conditions, and it is observed that the colour difference increases depending on the MW power applied from 90 W to 180 W, then a slight decrease occurs up to 270 W level, but then the colour difference increases again. It was also observed that the samples subjected to MW treatment and subsequent centrifugation at low speed showed a wider range of color difference than the samples centrifuged at high speed.

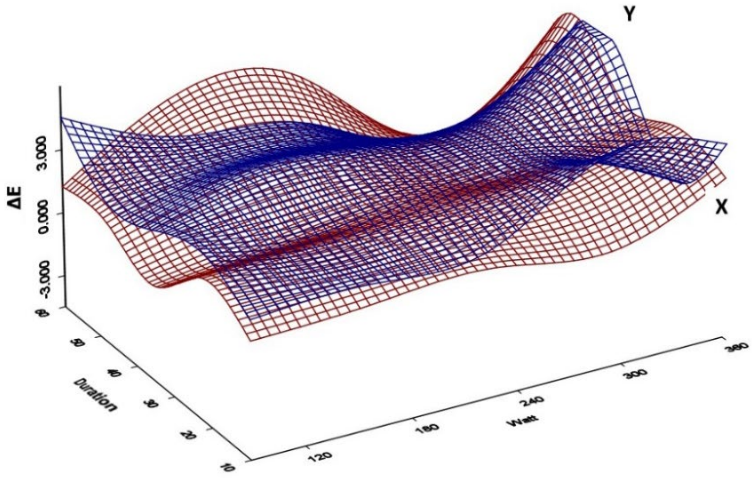

Figure 8. Effect of MW time and power on the total color difference values of the samples.

Figure 9 shows the relationship between the ΔE of the MW treated water samples. The colour difference relationship of the low speed centrifugation and MW treated water samples was R^2: 0.654, which was higher than that of the high speed centrifugation samples (R^2: 0.2612). It can be concluded that the colour difference values of the wastewater samples centrifuged at low speed as a result of MW treatment are more compatible with the process parameters than the control sample.

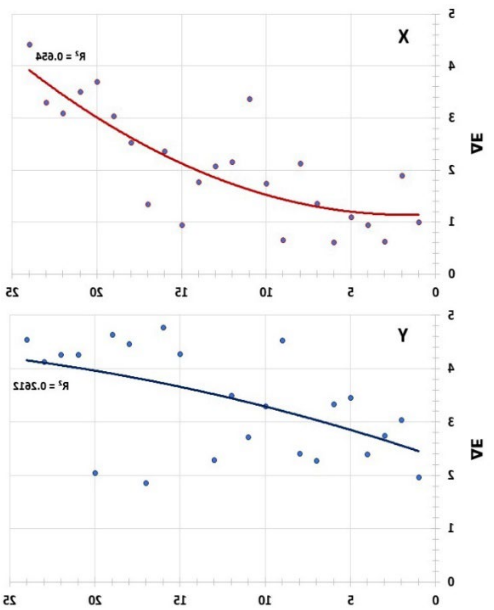

Figure 9. Total colour difference distributions of MW treated samples.

4. Conclusion

This study examined the effects of microwave (MW) irradiation on the physical properties of wastewater generated from the paper recycling process, particularly in terms of turbidity and color removal. The results demonstrated that MW irradiation had significant effects on both turbidity reduction and color modification, indicating that it has strong potential as an effective pre-treatment method for industrial wastewater management. The findings indicated that increasing MW power and irradiation duration resulted in greater reductions in turbidity. It is clear that MW irradiation as a promising and effective pre-treatment method for wastewater generated from paper recycling. The combination of MW treatment and centrifugation may offer a viable alternative to conventional physical and chemical treatment methods, particularly in reducing turbidity and improving color quality in wastewater. Future research could focus on optimizing MW parameters to further increase the benefits of this approach, assessing long-term environmental impacts and investigating its implications in industrial applications.

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