



## A COMPARATIVE ANALYSIS OF THE ENERGY EFFICIENCY AND COLORFASTNESS PROPERTIES OF PAD-STEAM AND MICROWAVE FIXING METHODS IN ACRYLIC KNITTED FABRICS

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### Keywords

*Acrylic knit fabric,  
Microwave fixing,  
Pad-steam,  
Energy efficiency,  
Color fastness,*

### Abstract

The present study examined the energy efficiency and color fastness of acrylic knitted fabrics subjected to two distinct dyeing methodologies: pad-steam and microwave. Three formulations of dyes were prepared in light, medium, and dark shades using cationic dyes (Bezacryl Goldgelb GL 200, Rot GRL 180, and Blue GRL 300). The fabrics were subjected to treatment with microwave (800 W) and pad-steam (105 °C) processes for a duration ranging from 60 to 240 seconds. Color was measured using the CIE L\*a\*b\* system, and washing, rubbing, and light fastness were assessed ISO standards. The utilization of microwave technology has been demonstrated to enhance sustainability, with the potential to reduce processing time and energy consumption by up to 60%. However, the pad-steam method yielded greater color depth and enhanced lightfastness, particularly for darker tones. A linear relationship ( $R^2 = 1.000$ ) was determined between energy consumption and CO<sub>2</sub> emissions, and 3.73 kg of CO<sub>2</sub> was saved in 240 seconds with the microwave method. The results demonstrate that microwave curing is a robust alternative for sustainable textile applications.

## AKRİLİK ÖRME KUMAŞLARDA PED STEAM VE MİKRODALGA FİKSE YÖNTEMLERİNİN ENERJİ VERİMLİLİĞİ VE RENK HASLIĞI ÖZELLİKLERİNİN KARŞILAŞTIRMALI ANALİZİ

### Anahtar Kelimeler

*Akrilik örgü kumaş,  
Mikrodalga fikse,  
Ped steam,  
Enerji verimliliği,  
Renk haslığı,*

### Öz

Bu çalışmada, akrilik örme kumaşların pad-steam ve mikrodalga fikse yöntemleriyle boyanması sonucunda elde edilen kumaşların, enerji verimliliği ve renk haslığı özellikleri bakımından karşılaştırmalı analizi yapılmıştır. Bezacryl Goldgelb GL 200, Rot GRL 180 ve Blue GRL 300 katyonik boyarmaddeleri kullanılarak açık, orta ve koyu tonlarda üç farklı boya reçetesi hazırlanmıştır. Kumaşlar, belirli sürelerde (60–240 s) mikrodalga (800 W) ve pad-steam (105 °C) yöntemleriyle fikse edilmiştir. Renk ölçümleri CIE L\*a\*b\* sistemine göre yapılmış, yıkama, sürtme ve ışık haslığı testleri ISO standartlarına göre değerlendirilmiştir. Mikrodalga yönteminin, daha kısa işlem süresi ve %60'a varan enerji tasarrufu ile ekolojik açıdan daha avantajlı olduğu saptanmıştır. Pad-steam yöntemi ise özellikle koyu tonlarda daha yüksek renk derinliği ve daha iyi ışık haslığı sağlamaktadır. Enerji tüketimi ile CO<sub>2</sub> emisyonları arasında doğrusal ilişki ( $R^2 = 1.000$ ) tespit edilmiş, mikrodalga yöntemiyle 240 saniyede 3.73 kg CO<sub>2</sub> tasarrufu sağlanmıştır. Sonuçlar, mikrodalga fikse yönteminin sürdürülebilir tekstil uygulamaları açısından güçlü bir alternatif olduğunu göstermektedir.

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## Highlights

- The microwave fixation method provides energy savings of up to 60% compared to the pad-steam method.
- A perfect linear relationship ( $R^2 = 1.000$ ) has been identified between energy consumption and CO<sub>2</sub> emissions.
- Satisfactory fastness results have been achieved with microwaves for light and medium shades.

## Graphical Abstract

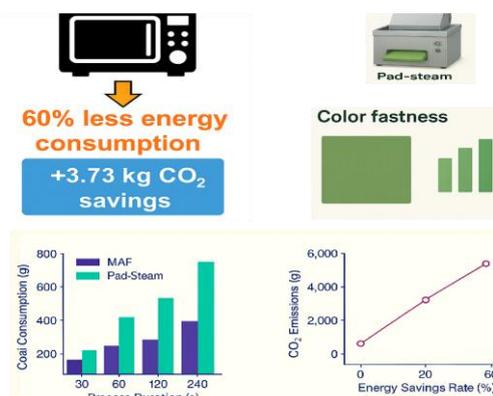


Figure. Graphical representation of the article

## Purpose and Scope

A comparison of pad steam and microwave fixation methods in acrylic knitted fabrics is necessary to determine whether the latter is a sustainable and more energy-efficient alternative. Such a comparison should take place in consideration of three factors: energy efficiency, color fastness, and environmental impacts.

## Design/methodology/approach

To evaluate the effectiveness of microwave-assisted and pad-steam fixation methods applied to acrylic knitted fabrics, a comparative experimental approach was employed. The samples were subjected to varying durations of fixation (30–240 s.), and their chromatic properties and colorfastness were evaluated according to ISO standards. Energy consumption and carbon dioxide (CO<sub>2</sub>) emissions were determined through calculation based on device power and the IPCC emission factors. Subsequent analyses were conducted statistically to compare energy efficiency and environmental performance between the two methods.

## Findings

The findings of the study indicate that the application of the microwave-assisted fixation method led to a 60% reduction in energy consumption and a concomitant decrease in carbon dioxide emissions when contrasted with the use of the pad-steam method. The findings from both methods demonstrated high washing, rubbing, and light fastness values. It was demonstrated by experimental application of microwave energy that a brighter and lighter hue was yielded. Conversely, the pad-steam method produced a darker shade with greater intensity. A linear relationship ( $R^2 = 1.000$ ) was identified between energy consumption and CO<sub>2</sub> emissions. The findings of the present study demonstrate that the microwave method is a sustainable, energy-efficient, and environmentally friendly method.

## Originality

The primary objective of the present study is to systematically compare the microwave-assisted fixation method on acrylic knitted fabrics with the pad-steam method in terms of energy efficiency, color fastness, and environmental impacts.

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## 1. Introduction

The textile dyeing industry consumes large amounts of water and energy, and it produces wastewater with a high waste load at the end of the process. Dyeing processes involve water and auxiliary chemicals at high temperatures, and they are lengthy. Therefore, it is one of the most resource-intensive sectors. Reducing this environmental impact requires developing more sustainable and efficient dyeing methods, which is important both economically and ecologically. Recently, researchers have turned to microwave energy as an environmentally friendly technology in this field.

Microwaves are a type of electromagnetic radiation that, upon penetrating polar molecules, induce rapid oscillation in their bonds, particularly those of water molecules. This oscillatory phenomenon is the underlying mechanism that generates heat through molecular friction. This mechanism facilitates the concurrent production of energy throughout the material's volume, a departure from conventional methods that rely on the transfer of energy from the surface to the center (Metaxas & Meredith, 1983; Chandrasekaran et al., 2013). This principle of "volumetric heating" is predicated on the radical difference in heat transfer, which has been demonstrated to provide a significant reduction in processing times and a notable increase in energy efficiency.

The first studies on the use of microwave technology for textile dyeing were conducted in the 1970s. For instance, Delaney and Seltzer's (1972) study reported the potential of microwave energy for the fixation of woolen fabrics following pad-dyeing, with a notable reduction in processing time. In a similar vein, Metaxas, Catlow, and Evans (1978) examined the microwave-assisted fixation method and determined that it expedited the binding of dyes to diverse fiber types. Research has demonstrated that microwave energy facilitates accelerated dyeing processes with reduced energy and water consumption by enhancing heat and mass transfer within the fiber structure (Haji, 2022).

Since the 2000s, there has been an increase in the number of studies on the use of microwave energy for the dyeing of acrylic fibers. In their 2008 study, Nourmohammadian and Davoudzadeh demonstrated that microwave energy has a significant impact on the dyeability of acrylic fibers. Specifically, they found that microwave energy increases the dyeability of acrylic fibers, improves color yield, and significantly reduces process time. Moreover, El-Gabry et al. (2014) conducted a comparative study on functional finishing applications performed using advanced technologies, such as microwaves and plasma, on acrylic fibers. It was noted that the microwave process facilitates dye diffusion.

In their study, Popescu et al. (2019) examined the applicability of microwave-assisted dyeing processes for acrylic knitted fabrics. The researchers investigated whether this method is more environmentally friendly and sustainable than traditional dyeing methods. The researchers obtained satisfactory fluorescent colors on acrylic knitted fabrics using the microwave-assisted dyeing method. They stated that microwave energy is a more sustainable method because it reduces both dyeing time and energy consumption.

Acrylic and various types of fibers have been subjected to testing using microwave technology. As reported by Şahinbaşkan et al. (2017), polypropylene blends can be dyed with dispersive dyes using microwave energy. In a similar vein, Adeel et al. (2018) discovered that polyester fabrics that had undergone microwave pretreatment demonstrated enhanced color depth and fastness when subjected to dyeing with disperse yellow 211.

Haji et al. (2022) recently conducted a review study investigating the applicability of microwave energy in textile dyeing on different fibers and dyes. The study systematically evaluated the advantages offered by the microwave method. The study concluded that microwave energy accelerates dye diffusion, changes the microstructure of fibers, increases color yield, and improves fastness values. However, it also noted some limitations to the industrial-scale applicability of microwave energy, such as ensuring uniform heat distribution and designing large-scale machines.

This study evaluated microwave and pad-steam curing methods for acrylic knitted fabrics not only in terms of color yield but also multidimensional parameters such as energy consumption, CO<sub>2</sub> emissions, color and light fastness values, and color yield depending on processing time. While literature has examined microwave curing, no study has evaluated both methods on the same fabric, using the same dye recipes and for the same time intervals, and compared them through quantitative environmental analyses. This paper demonstrates that the microwave method provides approximately 60% energy and CO<sub>2</sub> savings, that light and rub fastnesses are at competitive levels, and that color behavior varies over time, making a unique contribution to both sustainable textile technologies and the understanding of curing mechanisms.

## 2. Material and Method

The cationic dyes used in the study are Bezacryl dyes belonging to the Bezama company. Bezacryl Goldgelb GL 200, Bezacryl Rot GRL 180, and Bezacryl Blue GRL 300 dyes were used to prepare the dye solutions.

The knitted fabrics utilized in the present study were woven on a semi-automatic V-bed flat knitting machine, employing RL flat knit 34/2 Nm 100% acrylic Aksa 4316 yarn. This process yielded fabrics with a weight of 280 g/m<sup>2</sup>. Prior to the application of dyes, the fabrics were subjected to a pre-washing procedure at a temperature of 60°C for a duration of 20 minutes. This pre-washing step involved the use of a non-ionic detergent at a concentration of 1 g/L and sodium carbonate (Na<sub>2</sub>CO<sub>3</sub>) at a concentration of 1 g/L. Following this pre-washing step, the fabrics underwent a series of rinses with cold water and were subsequently dried. The pieces were then cut into 10x10 cm sections for the dyeing process.

AYSOL PAY (Ayteks' polyacrylate-based emulsifier), AYWET NBB (Ayteks' nonionic-based wetting agent), acetic acid for pH adjustment, and guar gum as a thickener were used as padding liqueur auxiliaries.

The dyeing process was executed via the Padbach method, commencing with the preparation of the dye bath. The pick-up ratio was calculated to be 70%. Three dye baths, comprising cationic dyes in light, medium, and dark shades, were meticulously prepared. The pH was adjusted to 4.5 using acetic acid. The fabrics were then passed through the prepared bath in the pad machine and then squeezed between two rollers to absorb the liquor. The pick-up ratio was controlled by the pressure setting of the pad rollers and the fabric's absorbency. The result was that the fabric absorbed liquor equal to 70% of its dry weight using the formula below.

$$AF = \frac{W_2 - W_1}{W_1} \times 100 \quad (1)$$

AF = Amount of flottant absorbed

W1 = Weight of dry textile product

W2 = Weight of impregnated textile product

A comparative analysis of microwave and traditional steam-fixing methods was conducted by preparing three distinct dyeing recipes, as outlined in Table 1. The recipes were meticulously formulated to yield a range of skin tones, encompassing light, medium, and dark complexions. The fabrics impregnated with the dye solution were subjected to fixation using two distinct techniques. First microwave fixation at 800 W and second conventional thermal fixation in a laboratory-scale machine operating at 105 °C. Fixation was performed at predetermined durations of 60, 90, 120, 150, 180, 210, and 240 seconds.

Following the dyeing process, the samples underwent a 30-minute wash cycle comprising 0.6 g of ECE soap and 0.15 g of sodium perborate, dissolved in 150 mL of water at a temperature of 50°C. The samples were then rinsed twice with cold water at the conclusion of the washing cycle.

**Table 1.** Padsteam dyeing recipies

Component	Light Shade	Medium Shade	Dark Shade
<b>Additives</b>	500 mL water + 1 g/L Wetting Agent + 0.5 g/L Guar Gum + 1 g/L Emulsifier	500 mL water + 1 g/L Wetting Agent + 0.5 g/L Guar Gum + 1 g/L Emulsifier	500 mL water + 1 g/L Wetting Agent + 0.5 g/L Guar Gum + 1 g/L Emulsifier
<b>Goldgelb GL 200</b>	1 g	2.5 g	5 g
<b>Rot GRL 180</b>	1 g	2.5 g	5 g
<b>Blue GRL 300</b>	1 g	2.5 g	5 g

## 2.1. Washing fastness tests

The evaluation of washing fastness was conducted in accordance with the color fastness method (ISO 105 C06), with a focus on domestic and commercial laundering procedures. This method is employed to assess the color change of textiles or garments during the washing process and the stain resistance of other textile components of the same product. For the test, 4 mm x 10 mm samples were prepared using multifiber fabric cut to the same dimensions and sewn together along one short edge. A series of washing tests were conducted using a wash fastness tester at a temperature of 50°C for a duration of 45 minutes. A wash solution was prepared with 4 g/L ECE detergent, and 150 mL of this solution was used for each sample. In addition, 50 steel balls with a diameter of 0.6 mm were placed in the tubes. These steel balls provided friction with the solution and the prepared test samples. Subsequent to the washing process, the samples were subjected to drying in a drying oven maintained at a temperature below 60°C. Thereafter, the samples were evaluated in a light cabinet using a gray scale.

## 2.2. Rubbing fastness test

To ascertain the color fastness of the resulting textile products to dry or wet rubbing, samples with dimensions of 140x50 mm were tested using a crockmeter with a rubbing head diameter of 16 mm and a pressure of 9 N, in accordance with the ISO 105 X12 standard.

## 2.3. Light fastness test

Given the exposure of textiles to sunlight, color fastness is of paramount importance. The ability of a fabric to withstand the effects of sunlight without discoloration is referred to as light fastness. The light fastness of the test samples was analyzed in accordance with the ISO 105-B02 method. This method is employed to ascertain the manner in which the color of any textile product is altered when subjected to an artificial light source (Xenon arc) that emulates natural daylight. Samples measuring 4.5 x 1 cm were affixed onto opaque cardboard, and the results were interpreted according to the blue wool scale. The test was terminated at the point where the amount of fading of the sample reached the Blue Wool Grade 6 level.

## 2.4. Color measurements of dyed samples

Color measurements of dyed fabrics were obtained through the utilization of the Macbeth COLOR-EYE 7000 spectrophotometer in accordance with the CIE L\*a\*b method. The CIE L\*a\*b method is a color space method that quantifies and describes a color as perceived by the human eye. The primary objective of this instrument is to quantitatively assess the disparities in color perception in relation to human visual perception. This model utilizes a three-axis coordinate system to delineate colors. The method delineates colors through the utilization of three components: L\* (0-100, where L=0 is black and L=100 is white), a\* (the green-red axis), and b\* (the blue-yellow axis). The primary objective of the CIE L\*a\*b\* system is to objectively and quantitatively assess color differences through the calculation of the perceived difference between two colors, known as the Delta E ( $\Delta E^*$ ), which quantifies the geometric distance between their respective coordinates.

## 2.5. Energy and environmental assessment

Energy consumption calculations were performed by multiplying the technical power ratings (Watts) of the devices used in the microwave and pad-steam fixation methods by the processing times (seconds). The results were expressed in Joules. For the microwave fixation method, the device power was directly multiplied by the time. For the pad-steam method, the steam generator energy consumption was calculated based on manufacturer data. The energy and emission data were obtained from triplicate experiments and statistically compared using the Student t-test. The relationship between energy consumption and CO<sub>2</sub> emissions was assessed using the Pearson correlation coefficient.

A correlation analysis was conducted to ascertain the relationship between energy consumption and colorimetric parameters. The Pearson correlation coefficient function was utilized to facilitate this analysis. Additionally, a comparative analysis of energy efficiency was conducted among the various methods employed, with the calculation of fundamental statistical parameters such as mean, standard deviation, and variance.

The calculation of carbon dioxide (CO<sub>2</sub>) emissions was conducted in accordance with the guidelines established by the Intergovernmental Panel on Climate Change (IPCC) and fuel-specific emission factors particular to Turkey. The emission factor employed for CO<sub>2</sub> emissions from coal combustion was 3.67 kg CO<sub>2</sub>/kg coal.

All experimental procedures, measurements, and calculations were performed in accordance with laboratory-scale repeatability and reliability standards. The methodology under consideration provides two key contributions. First, it offers precise measurements of energy and environmental performance. Second, it provides a robust framework for evaluating sustainable laboratory practices. The methodology highlights the potential of microwave-assisted techniques in reducing carbon footprints while maintaining operational efficiency.

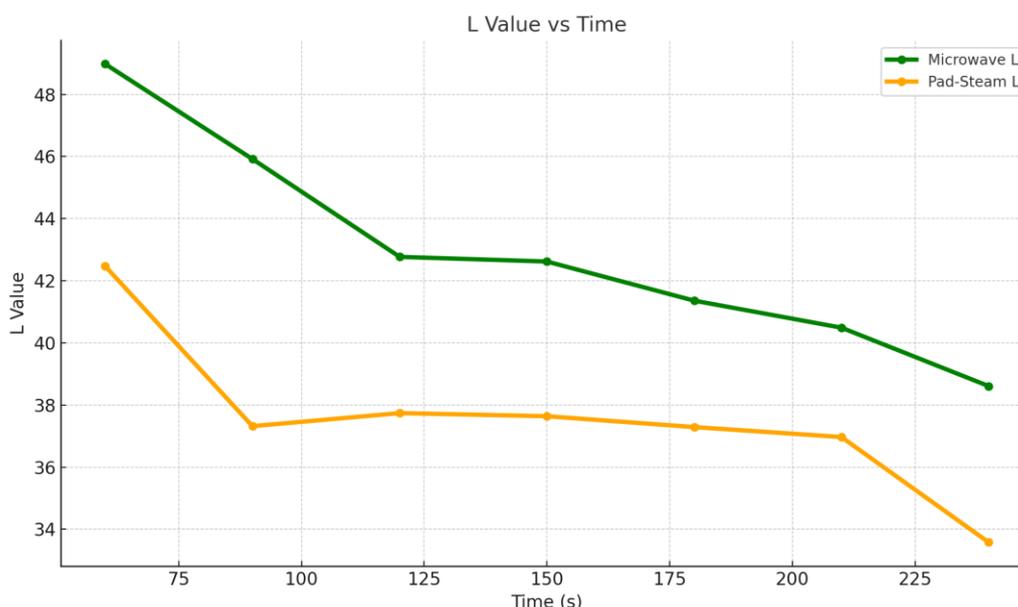
## 3. Results

As illustrated in **Table 2**, the CIE L\*a\*b\* values of light colors were obtained through the processes of microwave and pad steam fixation. For the purpose of facilitating a visual comparison, a comparative graph of color lightness and darkness values, along with L values, is plotted in **Figure 1**.

**Table 2.** CIE Lab values of light colors obtained as a result of microwave and Pad steam fixation

Time (s)	Microwave L	Microwave a	Microwave b	Pad-Steam L	Pad-Steam a	Pad-Steam b
60	48.98	20.87	13.39	42.47	17.42	7.92
90	45.92	20.70	9.87	37.32	21.96	9.54
120	42.77	19.65	11.79	37.74	19.80	9.07
150	42.62	18.12	7.26	37.64	19.09	5.80
180	41.36	21.48	11.53	37.29	16.14	7.63
210	40.49	21.04	11.21	36.97	16.20	6.80
240	38.61	20.61	7.32	33.58	15.80	7.30

A thorough examination of the data presented in the table and graph indicates that the pad-steam method consistently results in a decrease in brightness (L) values as the duration of the process increases. This effect leads to enhanced dye fixation and the production of darker colors. In contrast, the microwave method yields lighter tones, characterized by higher L values. In regard to chromatic properties, both methodologies manifest reddish-yellow characteristics (positive a\* and b\* values), yet the microwave approach yields a color that is both warmer and more vivid, exhibiting notably higher a\* and b\* values compared to the pad-steam method. The plateauing of L\* values in the pad-steam method after 90 seconds indicates that the process time can be optimized.



**Figure 1.** Comparison of L values obtained after microwave and pad steam fixation of light colors

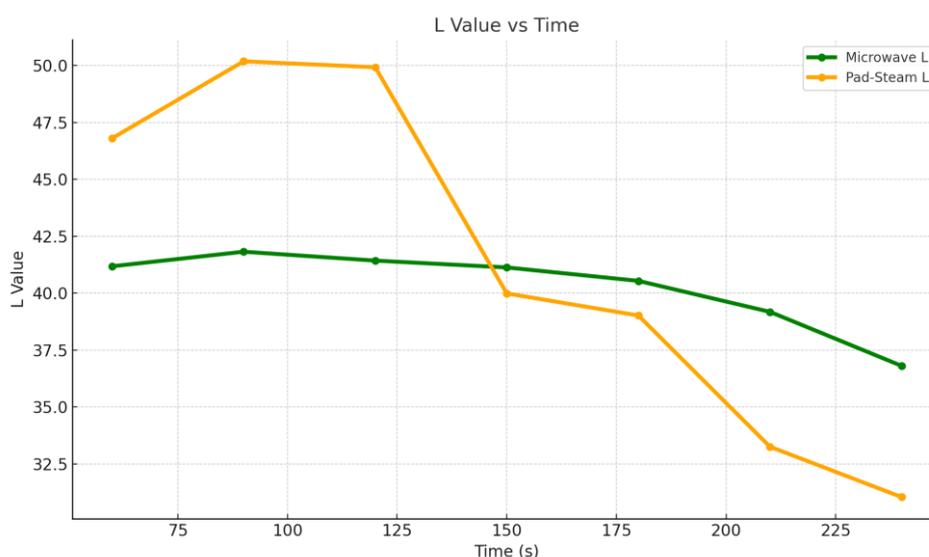
In summary, the selection of either method is contingent upon the specific aesthetic and technical requirements of the given scenario. The microwave method is particularly effective when it comes to lighter and brighter tones, while the pad-steam technique is especially advantageous for applications requiring darker and deeper colors. The capacity of the CIE L\*a\*b\* system to quantitatively assess color variations in such comparative analyses underscores its significance in the optimization of textile dyeing processes. Patel et al. observed in their study that, while the microwave method offers an environmentally friendly dyeing process using natural dyes, pad-steam has the advantages of lower equipment costs and easier process control. This comparison underscores the viability of microwave-assisted dyeing as a sustainable and efficient alternative, while pad-steam remains a preferred method due to its cost and stability advantages (Patel et al., 2019).

**Table 3.** CIE Lab values of medium colors obtained as a result of microwave and Pad steam fixation

Time (s)	Microwave L	Microwave a	Microwave b	Pad-Steam L	Pad-Steam a	Pad-Steam b
60	41.18	22.99	22.99	46.80	20.31	14.54
90	41.82	22.97	22.25	50.18	20.58	19.83
120	41.43	22.83	22.52	49.92	22.51	19.44
150	41.13	23.61	18.46	39.99	19.88	13.22
180	40.54	21.56	16.33	39.02	18.35	11.92
210	39.18	22.62	17.68	33.26	17.26	11.34
240	36.81	22.24	17.13	31.05	19.18	10.57

The CIE Lab values for the medium-dark colors shown in Table 3 were obtained by microwave and pad steam fixation. For visual comparison, a comparative graph of the lightness and darkness values and L values is shown in Figure 2.

The comparative analysis of CIE L\*a\*b\* values presented in Table 3 illuminates the color properties of mid-tone acrylic fabrics undergoing processing via microwave and pad-steam fixation methods, contingent upon varying temporal parameters. A thorough examination of the L (lightness) values reveals that the samples subjected to the microwave fixing method undergo a gradual darkening over time, with a decrease from L: 41.18 to L: 36.81. In contrast, the pad-steam method initially yields a higher light color tone (L: 50.18 at 90 seconds). However, a marked darkening trend is observed as the duration increases (L: 31.05 at 240 s). Conversely, the a (redness-greenness) and b (yellowness-blueness) values illustrate variability in both methodologies. This indicates that the color tones are sensitive to the fixation time. It is understood that the microwave method provides more stable and balanced color distribution, while the pad-steam method penetrates more deeply with the effect of humidity and diffusion and produces darker tones over time. In light of these data, microwave-assisted fixation offers not only speed and energy efficiency, but also superior process control and a distinct color profile, offering an innovative alternative to traditional methods. The lighter color tone (higher L\*) that results from this process is not a disadvantage; rather, it is an indication of enhanced process control and the prevention of undesirable excessive darkening.



**Figure 2.** Comparison of L values obtained after microwave and pad steam fixation of medium colors

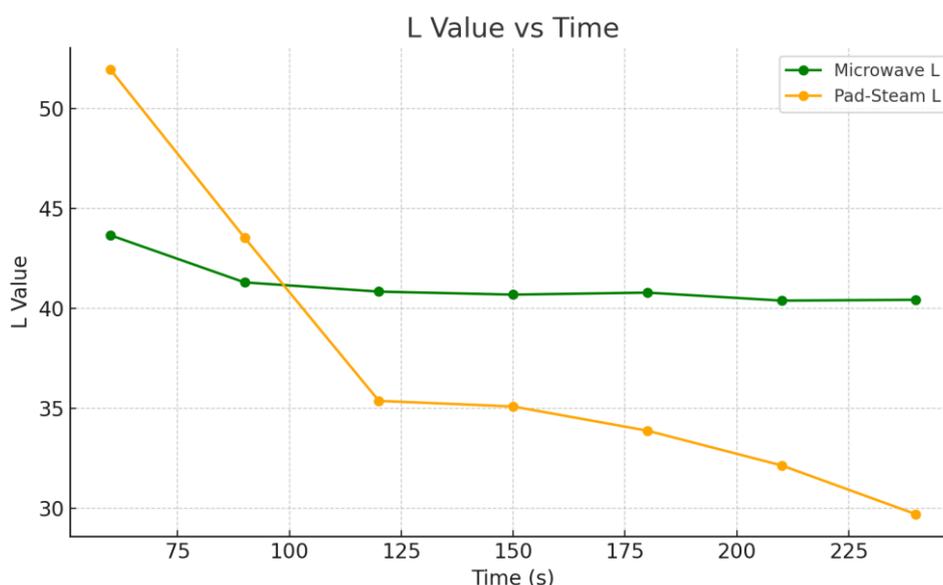
The findings indicate that the pad-steam technique is more efficacious in terms of color efficiency, whereas the microwave method is more effective in terms color vibrancy, particularly for red and yellow tones. The employment of either technique for dyeing acrylic fabrics is deemed permissible; nevertheless, the selection of a method may be contingent upon production objectives, environmental impacts, and costs. The microwave approach is distinguished by the expeditiousness of the process, the energy efficiency of the apparatus, and its environmental friendliness. In contrast, the pad-steam method is characterized by its cost-effectiveness and adaptability to various fabric applications. A thorough evaluation of the merits and limitations of both methods is therefore essential. The most suitable method should be selected based on the specific requirements of the production context. Gholami and Nourmohammadian (2008) stated that dyeing processes performed using microwaves are completed in a shorter time and consume less energy compared to traditional methods. They also reported that higher color density (K/S) is achieved in microwave-based dyeing processes. The results of their study, which indicated that this enables the fabric to take on more vivid and brighter colors, are consistent with our study.

**Table 4.** CIE Lab values of dark colors obtained as a result of microwave and Pad steam fixation

Time (s)	Microwave L	Microwave a	Microwave b	Pad-Steam L	Pad-Steam a	Pad-Steam b
60	43.67	23.98	18.47	51.96	22.27	19.18
90	41.31	23.91	16.85	43.54	23.45	17.01
120	40.85	24.57	17.92	35.38	22.52	12.50
150	40.70	23.03	48.47	35.10	20.84	12.74
180	40.80	22.81	26.46	33.89	21.89	11.68
210	40.40	23.79	15.96	32.15	21.04	11.97
240	40.44	22.84	19.35	29.71	18.84	9.46

The values that were obtained from the CIE Lab for dark colors, which were derivatively obtained from the microwave and pad-steam curing processes, are presented in **Table 4**. A comparative graph is also provided in **Figure 3**. A meticulous evaluation of the data exhibited in the table and graph evinces discernible disparities between the two methods with respect to color intensity and homogeneity.

The microwave method demonstrated a diminished scope of modifications in L values (43.67–40.44) across the 60- to 240-second timeframe. The results of this investigation indicate that microwave curing produces more stable color density in darker shades and maintains uniform heat distribution. This finding aligns with the outcomes of a 2019 study conducted by Jang et al., which demonstrated that microwave curing expedites diffusion equilibrium by facilitating uniform thermal conductivity in a relatively brief time frame. In contrast, the pad-steam curing process commences from an initial value of L=51.96 in 60 seconds and undergoes a decrease to L=29.71 in 240 seconds. The findings of the present investigation demonstrate a considerable increase in color depth over time in response to steam setting. This suggests an augmented capacity on the part of the fabric to absorb dye. However, the slope of the curve indicates a more uneven color recovery in comparison to the microwave method. This phenomenon may be interpreted as a marked increase in dye migration occurring during the steam setting process.



**Figure 3.** Comparison of L values obtained after microwave and pad steam fixation of dark colors

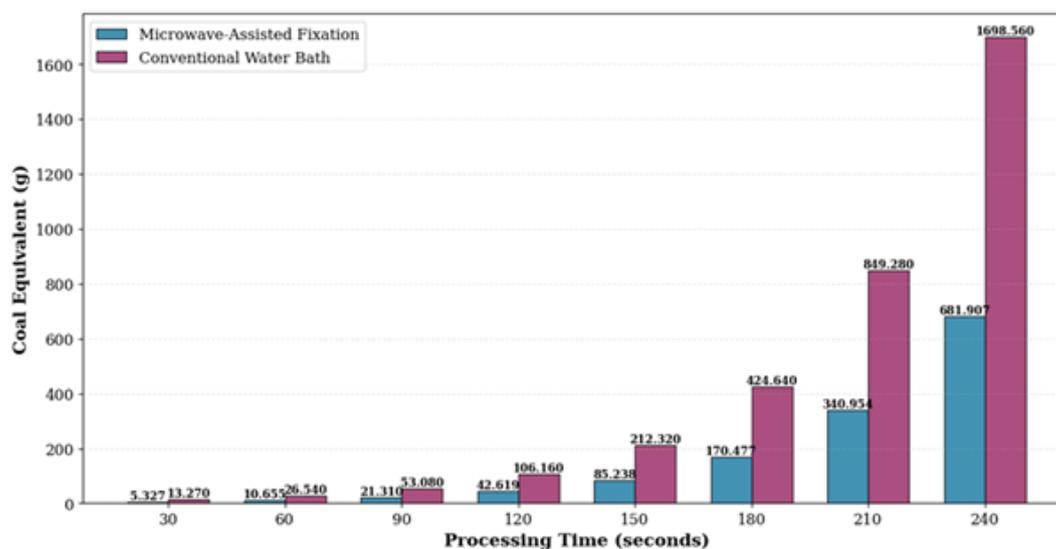
The washing, rubbing, and light fastness values of acrylic fabrics dyed using the microwave and padsteam methods are shown in **Table 5**. The two methodologies exhibited high washing fastness, particularly in light and medium hues, thereby suggesting that the dyes exhibited a high degree of adhesion to the fiber. In both dry and wet conditions, the rubbing fastness results generally reached a level of 5. However, slight decreases in dark shades (4–4.5) were observed upon utilization of the microwave method. This phenomenon is attributable to the augmented deposition of pigments upon the fiber's exterior, manifesting in deeper coloration patterns

**Table 5.** Fastness properties of acrylic fabrics

Method	Shade	Washing Fastness							Rubbing Fastness		Light Fastness Rating
		CC	W	A	P	PA	C	Ac	Dry	Wet	
Microwave	Light	5	5	5	5	5	5	5	5	5	5
Microwave	Medium	5	4-5	5	5	4-5	5	5	5	4-5	5
Microwave	Dark	4-5	4-5	5	5	4-5	4-5	5	4-5	4	4
Pad-Steam	Light	5	5	5	5	5	5	5	5	5	6
Pad-Steam	Medium	5	4-5	5	5	5	5	5	5	4-5	5
Pad-Steam	Dark	5	4	5	5	4-5	4-5	5	4-5	4-5	4

The findings of the study indicate that the pad-steam method demonstrates superior performance in light shades when compared to the microwave method. This phenomenon can be attributed to the prolonged fixation time of the dye molecules in the pad-steam fixation process, a consequence of the effects of moisture and steam. For darker tones, light fastness values decrease to 4–4.5 with both methods, consistent with the frequently emphasized fact in the literature that darker colors are more susceptible to photodegradation (Handbook of Textile and Industrial Dyeing). The utilization of microwaves as a technique has been demonstrated to be a rapid and energy-efficient

approach. Conversely, the application of pad-steam has been shown to offer enhanced light stability, particularly in lighter tones. This attribute renders pad-steam a potentially favorable option for applications in outdoor settings.



**Figure 4.** Coal consumption chart

**Figure 4** shows the coal consumption chart in grams. Comparative analysis reveals a consistent exponential growth trend in coal consumption for both fixation methods. Microwave-assisted fixation demonstrates significantly lower energy requirements across all process durations. According to the results obtained, the microwave method yielded consumption values ranging from 5.33 to 681.91 g in the 30–240 s range, while the traditional water bath method yielded values ranging from 13.27 to 1,698.56 g. This provides an advantage of approximately 2.5:1 and shows that the microwave technique offers approximately 60% improvement in energy efficiency. When using a 3.67 kg CO<sub>2</sub>/kg coal emission factor, the microwave method demonstrates a significantly lower carbon footprint across all processing times. Microwave fixation produced values between 19.55 and 2,502.60 g CO<sub>2</sub>, while the water bath method generated emissions in the range of 48.70 to 6,233.72 g. The perfect linear relationship between energy consumption and CO<sub>2</sub> emissions ( $R^2 = 1.000$ ) indicates that emission reductions are directly linked to energy savings. An average emission reduction of 60.02% demonstrates significant environmental benefits in laboratory-scale applications, with a reduction of 3.73 kg in 240-second cycles indicating significant sustainability potential.

**Figure 5** shows the CO<sub>2</sub> emission comparison of both methods. When using a 3.67 kg CO<sub>2</sub>/kg coal emission factor, the microwave method demonstrates a significantly lower carbon footprint across all processing times. Microwave fixation produced values between 19.55 and 2,502.60 g CO<sub>2</sub>, while the water bath method generated emissions in the range of 48.70 to 6,233.72 g. The perfect linear relationship between energy consumption and CO<sub>2</sub> emissions ( $R^2 = 1.000$ ) indicates that emission reductions are directly linked to energy savings. An average emission reduction of 60.02% demonstrates significant environmental benefits in laboratory-scale applications, with a reduction of 3.73 kg in 240-second cycles indicating significant sustainability potential.

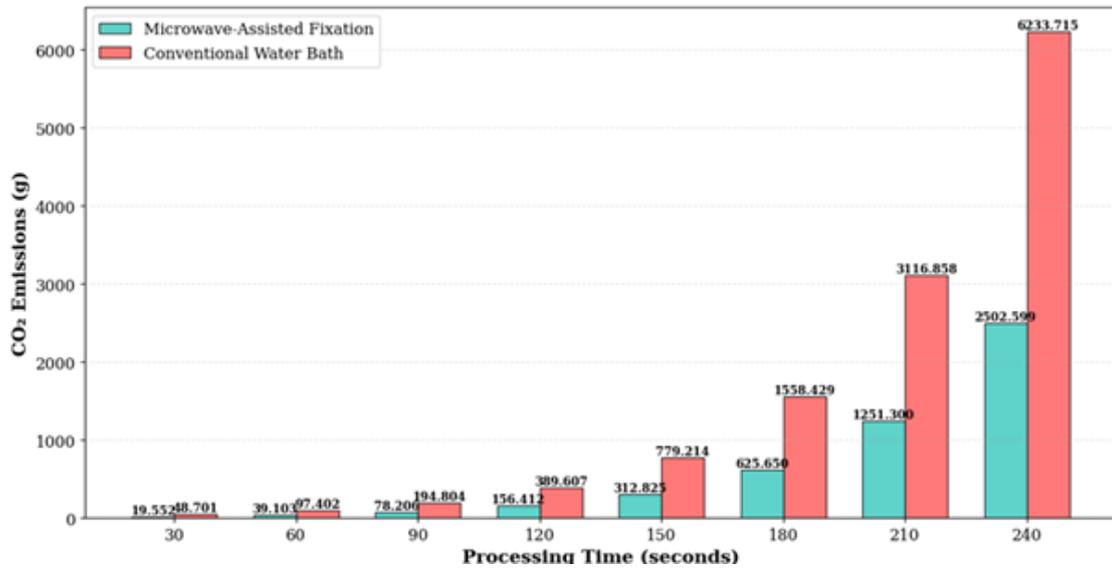


Figure 5. CO<sub>2</sub> Emission Comparison Chart (g)

Figure 6 shows the energy savings rate analysis. The energy savings rate remained constant throughout all process durations at 59.85%, demonstrating that the microwave-assisted method provides consistent efficiency improvements regardless of duration. This temporal invariance offers predictability advantages in terms of energy budgeting and enables accurate calculations in life cycle assessments.

**Energy Efficiency of Microwave-Assisted Fixation Method**

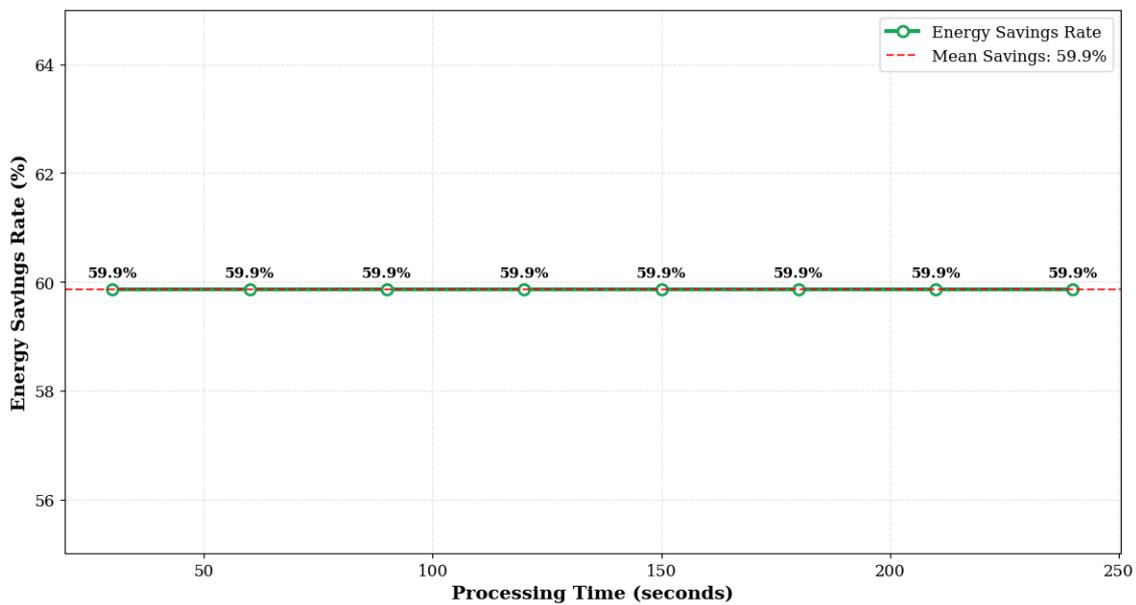


Figure 6. Energy savings rate analysis

Figure 7 shows CO<sub>2</sub> footprint analysis of microwave fixing. The energy savings rate remained constant throughout all process durations at 59.85%, demonstrating that the microwave-assisted method provides consistent efficiency improvements regardless of duration. This temporal invariance offers predictability advantages in terms of energy budgeting and enables accurate calculations in life cycle assessments.

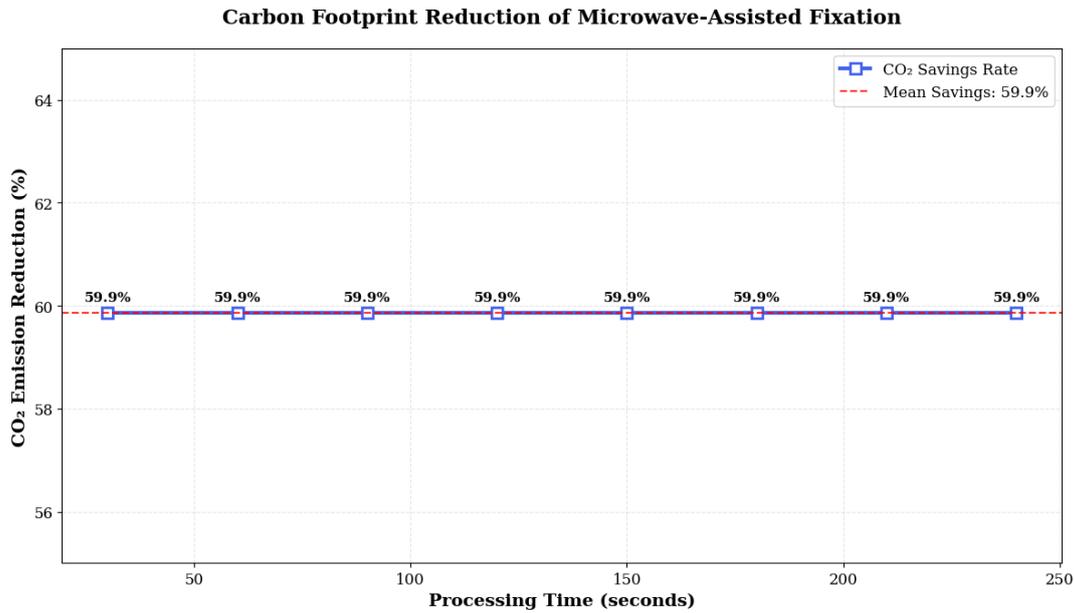


Figure 7. Carbon footprint of microwave fixation

### 3.1. CO<sub>2</sub> Savings Rate Analysis

Figure 8 shows coal consumption depending on process time. As can be seen from the figure, the microwave fixation method requires less energy and therefore less coal consumption than the traditional method. In parallel with the energy savings profile, the CO<sub>2</sub> emission reduction rate also remained constant under all experimental conditions, achieving a level of 59.85%. This result confirms the direct correlation between energy consumption and carbon emissions and demonstrates that gains in energy efficiency translate directly into environmental benefits.

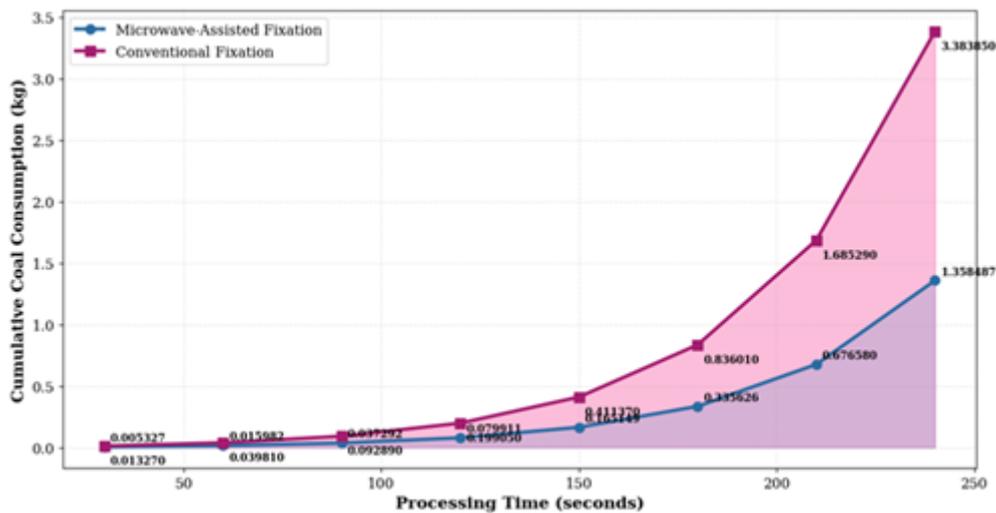


Figure 8. Cumulative coal consumption of different fixation methods

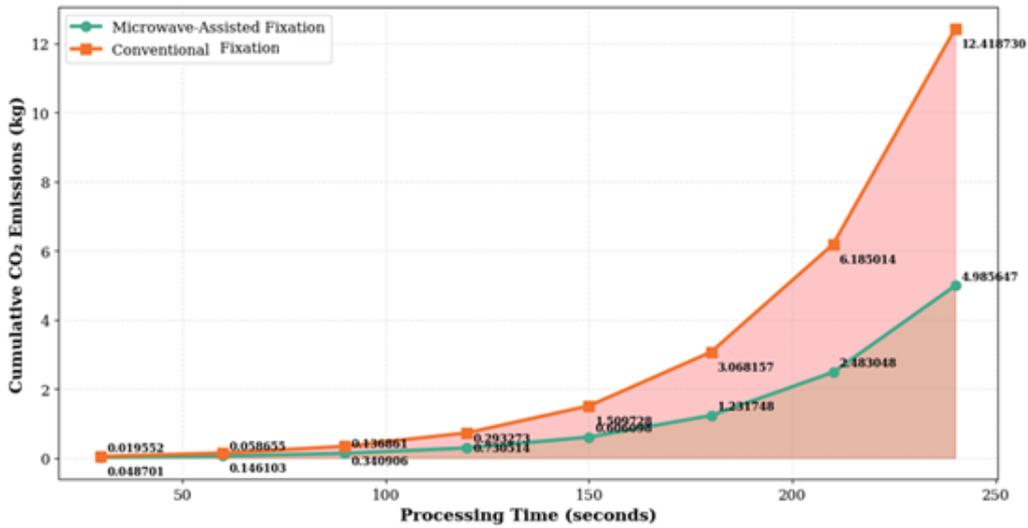


Figure 9. Cumulative CO<sub>2</sub> emissions of different fixation methods

### 3.2. Cumulative CO<sub>2</sub> Emission Profile

Figure 9 shows the CO<sub>2</sub> emissions of different fixation methods. The microwave method causes less CO<sub>2</sub> emissions because it consumes less coal. Cumulative CO<sub>2</sub> emission curves show similarities with energy consumption patterns, and the microwave method achieves a reduction of 3,731 kg CO<sub>2</sub> at the end of 240 s. The cumulative difference increases over time, demonstrating the long-term environmental benefits of the microwave method and showing full compliance with the linear emission model. This finding shows that microwave technology can make significant contributions to sustainability, especially in long-term usage scenarios.

### 3.3. Logarithmic Scale Comparison

Both graphs in Figure 10 clearly demonstrate that the microwave fixation method saves energy and reduces the carbon footprint. The logarithmic scale makes the environmental impact of the pad steam method more evident, especially with longer processing times. These findings support microwave technology as a strong alternative for green chemistry and sustainable textile applications. Analysis on a logarithmic scale reveals that consumption growth shows parallel trends for both methods, yielding an identical exponential growth rate (slope = 0.0087). These parallel log-linear trends confirm that the relative efficiency advantage of microwave technology remains constant regardless of absolute consumption levels. Therefore, this relationship demonstrates that the proportional efficiency between methods is preserved at different scales and that reliable predictions can be made for longer processing times.

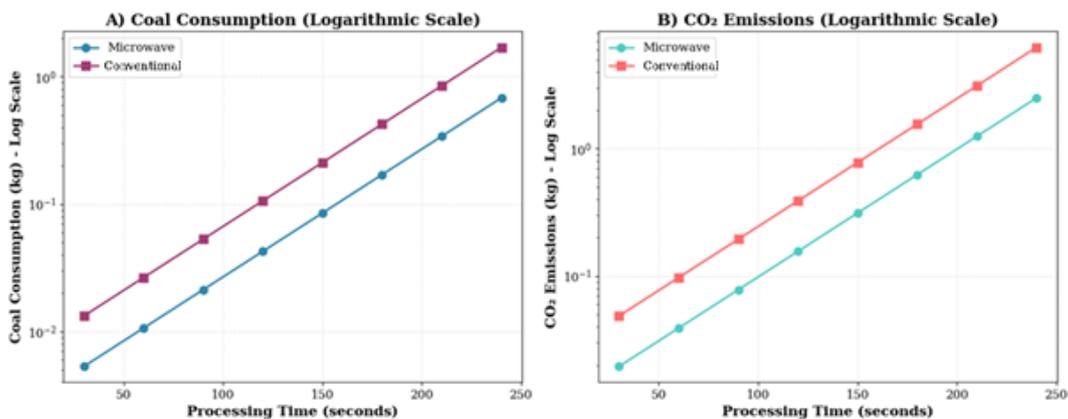


Figure 10. Logarithmic comparison of coal consumption and CO<sub>2</sub> emissions

#### 4. Result and Discussion

A comparative analysis of the microwave and pad-steam fixation methods for dark-colored samples reveals significant differences in color strength stability, energy utilization, and process homogeneity. It was determined that the microwave fixation system exhibited relatively stable lightness levels across the entire 60–240 s range, indicating uniform dye diffusion and minimized color migration, based on the obtained CIE L values. This finding is consistent with the results reported by Jang et al. (2019), who observed that microwave-assisted fixation facilitated rapid and homogeneous thermal transfer, thereby reducing dyeing variability and enhancing process reproducibility.

Conversely, the pad-steam process demonstrated a marked decline in L values (from 51.96 to 29.71) as fixation time increased. This phenomenon suggests a heightened dye uptake and the development of more pronounced coloration; nevertheless, the precipitous incline of the curve signifies a less regulated coloration mechanism, with the possibility of disparate dye penetration. The broader fluctuation in a and b coordinates within pad-steam samples lends further support to the presence of non-uniform color distribution and potential over-migration of dye molecules, particularly at higher exposure durations.

From a technological standpoint, microwave heating provided a more energy-efficient and environmentally sustainable alternative, requiring shorter fixation times to achieve comparable or superior color depth. This outcome aligns with the prevailing consensus that microwave systems exhibit a reduction in water and energy consumption while maintaining high fixation efficiency (Zhang et al., 2020).

A comprehensive analysis of the available data unequivocally demonstrates that microwave fixation emerges as a preeminent alternative for dark shade dyeing, exhibiting superior control over lightness, enhanced reproducibility, and augmented ecological performance. However, it is imperative to optimize the parameters of microwave exposure time and field intensity to prevent surface overheating or thermal degradation of dye molecules. Future studies should further explore hybrid processes that integrate microwave pre-activation with conventional steaming to maximize dye utilization and minimize environmental impact.

Preliminary experimental analyses have demonstrated that the microwave-assisted fixation method exhibits significant advantages over the traditional water bath method with respect to energy consumption and associated environmental impacts. An analysis of coal consumption data reveals that the microwave method requires approximately 60% less energy throughout all process times. This efficiency advantage can be attributed to the minimization of thermal losses thanks to the direct dielectric heating mechanism.

A direct correlation exists between energy consumption and CO<sub>2</sub> emissions. The employment of the microwave method resulted in a mean CO<sub>2</sub> emission reduction of 59.85%, accompanied by a maximum reduction of 3.73 kg over a 240-second processing duration. The constant energy and emission savings rates demonstrate the method's scalability, independent of processing time. This provides a reliable basis for carbon accounting.

Cumulative consumption and emission profiles demonstrate that the discrepancy between the methods becomes more evident over time, suggesting that the economic and environmental advantages of the microwave-assisted technique will be more pronounced in long-term or high-volume processes. Logarithmic-scale evaluations confirmed that both methods exhibited similar growth rates; however, the microwave method maintained its relative advantage independently of absolute consumption levels.

The findings generally indicate that microwave-assisted fixation offers significant gains in terms of both energy efficiency and environmental sustainability at the laboratory scale. This approach is noteworthy as a robust alternative for sustainable laboratory practices, contributing meaningfully to the reduction of the carbon footprint and the enhancement of operational efficiency. The demonstrated benefits justify the consideration of microwave-assisted methods in green chemistry initiatives and sustainable laboratory practice guidelines.

Subsequent studies employing life cycle assessment to investigate additional environmental impact categories will facilitate a comprehensive sustainability evaluation of microwave-assisted laboratory techniques.

It is recommended that the following be considered:

- It is imperative to investigate the applicability of the microwave method to a range of laboratory processes.
- It is imperative that sensitivity analyses be performed on different coal types and variable emission factors.

- It is imperative that the full environmental impact of the methods be assessed using Life Cycle Assessment (LCA).

The present study has demonstrated, through the use of quantitative data, that microwave technology can not only increase energy efficiency in laboratory processes but also make significant contributions to environmental sustainability.

### Conflict of Interest

No conflict of interest was declared by the authors.

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