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OPTIMIZATION OF WOOD-BASED BIRCH PLYWOOD CO_2 LASER ENGRAVING PROCESS PARAMETERS WITH TAGUCHI METHOD

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Abstract: In this study, the optimization of the parameters used in the engraving process of wooden birch plywood material with a CO_2 laser machine was investigated using the Taguchi method. An industrial laser machine with a 150W glass tube was used during the experimental examination process. There are basic factors affecting the engraving process of wooden surfaces such as laser power (P), engraving speed (S) and laser head parts (F). The engraving depth (D) and engraving width formed on the surface during the engraving process are the main factors that determine the aesthetics of the product. Taguchi L25 orthogonal array was used in the experiments to determine and optimize the highly important parameters. The optimum combination of parameters in the laser engraving process was then evaluated. The research results showed that the effect of P and S factors played a leading role, and the F parameter had a small effect on the depth of wood scraping. Optimization results found that F:5, S:100 and P:30 gave the best engraving depth optimization, while F:6, S:300 and P:10 gave the lowest engraving depth optimization result.

Keywords: Taguchi method, parameter optimisation, CO_2 laser, wood carving, birch plywood

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1. Introduction

Wood is one of the most abundant materials in nature and has superior properties compared to other building materials (Oğurlu, 2024). Wood is a renewable material with low density, low thermal conductivity, high mechanical strength, easy workability and good aesthetic appearance. (Kurt and Can, 2021). Medium density fiberboard and plywood are generally used in wood laser engraving. Birch plywood used in laser engraving is made by bonding birch veneers in single layers with opposite grain directions. Plywood obtained from birch wood has high quality, high resistance properties and sufficient hardness. However, high-quality birch veneers are used on visible surfaces in furniture, interior decoration panels, handicrafts and various special places (Çakıroğlu et al., 2018).

Laser cutting, which is frequently used in wood processing, creates high-cutting quality and smooth cutting surfaces unlike other thermal cutting methods. In these aspects, laser cutting is superior to other methods (Uzungörür, 2015). Laser light for marking, engraving, and surface cleaning in wood processing (Uzungörür, 2015, Kúdela, 2020) primary wood processing in automated systems (McMillin et al., 1984) and MDF (medium density fibreboard) cutting (Eltawahni et al., 2011) for the production of decorative and ornamental items. Laser machines are widely used in the furniture industry, decoration and ornaments production. However, to obtain a quality result with the laser cutting method, it is not enough to select the laser cutting machine suitable for the material to be cut. (Yaka et al., 2011). In addition to machine selection, cutting parameters such as cutting speed and gas pressure should also be determined appropriately. It is important to determine the cutting parameters correctly to complete the cutting process with minimum thermal damage (Uzungörür, 2015). Since laser machines do not contain cutting elements, they do not produce chips and dust, so they are more advantageous than other cutting methods. (Aniszewska et al., 2020). In CO_2-powered laser devices, high electrical voltage is applied to the carbon dioxide gas to cut. In addition, nitrogen and helium gas can be added to carbon dioxide gas to further increase efficiency. With the ease of obtaining the laser beam in this way, increases in application areas have been seen. The biggest reason for production with laser cutting is to minimise production error and to provide automation (Tunç, 2015).

In the cutting of plywood material with a CO_2 laser; it has been stated that focal length (Tayal et al., 1994), cutting speed (Gabdrakhmanov et al., 2019), laser power, laser gas and air pressure have an effect on the cutting (Çavdar and Tanrısever, 2013). Many studies have been carried out on the effects of beam power, polarisation, optical directions of the lens, and position of the focal point, gas spray support system, workpiece thickness, material density and moisture content in laser wood processing (Barnekov et al., 1986). Also, the effect of laser power cutting speed and the number of rings per year on the notch width at the top and bottom grades of the cutting notch (Kubovský et al., 2020) laser engraving properties of some wood and wood-based composite materials (Teivonen, 2016) current research has also been carried out.

When cutting wood with a CO_2 laser, optimization of parameters related mainly to laser performance and cutting speed is important. These parameters have significant effects on production efficiency and cutting quality (Ružiak et al., 2022). The factors affecting the laser cutting of wood can be divided into three groups; these are the characteristics of the radiation beam, laser power (P), cutting speed (V), focal point position, annual ring number, moisture content and density of the wood (Sinn et al., 2020).

This study aimed to investigate the best combination of laser engraving factors for birch plywood surfaces using ANOVA analysis of variance with L25 orthogonal Taguchi sequence design. In wood laser engraving, the width and depth of the engraving determine the light and dark tones of the resulting image. As the laser radiation power increases, the carving width and depth also increase. For example, when carving an image into wood, a shallow depth will cause the image to appear blurred and out of focus if the surface area increases. The findings of the study show that the effect parameters can be optimised to guarantee high-quality wood carving with the desired carving width and depth as well as the capacity to adapt to complex designs.

2. Materials and Methods

2.1. Taguchi Method

The Taguchi method is a powerful statistical approach often used for product and process optimisation that plays an important role in quality engineering. This method was developed by Japanese engineer and statistician Genichi Taguchi (Roy, 2010). The Taguchi method is an experimental analysis technique used to improve the quality and reduce the costs of product or process designs. The basic philosophy of the Taguchi method is to minimise variation in product or process performance due to the influence of uncontrollable factors (noise factors) (Phadke, 1995). This approach uses a strategy called "parameter design" to determine optimal levels of controllable elements. This makes the product or process performance more resilient to disruptive factors. One of the most important features of this method is the use of orthogonal arrays. By using orthogonal arrays, maximum information can be obtained with minimum experimentation (Taguchi et al., 2004). This saves a lot of time and costs. In addition, the Taguchi method optimises both average power and power variation simultaneously through signal-to-noise ratio (S/N) analysis. The application of the Taguchi method generally involves the following steps: Defining the problem, determining the control factors and control levels, selecting the appropriate orthogonal array, performing the experiment, analysing the data and determining the optimum conditions, and finally performing verification experiments. (Mehat et al., 2012, Güneş et al., 2024, Gökçe and Ersin, 2020, Nguyen et al., 2020). This method has wide applications in technical and industrial applications. In particular, effective results can be obtained in areas such as production process optimisation, product design, material selection and quality control (Shuster, 2007). Optimising the parameters of the CO_2 laser engraving process using the Taguchi method provides the opportunity to systematically analyse and optimise this complex process. This approach makes it possible to identify the important parameters in the laser engraving process and the optimum combination of these parameters. During the studies, the measured responses are converted into appropriate S/N ratios using three general classes "Highest is better in equation 1", " Lowest is better in equation 2" and "nominal is best in equation 3". The following equations are used to calculate S/N ratios for various quality attributes as follows.

$$\text{Highest best} \frac{S}{N} = -10\log(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}) \quad (1)$$

$$\text{Lowest best } \frac{S}{N} = -10\log(\frac{1}{n}\sum_{i=1}^{n} y_i^2) \quad (2)$$

$$\text{Nominal best} \frac{S}{N} = 10\log(\frac{\bar{y}}{S_y^2}) \quad (3)$$

2.2. Experimental Study

In the study, five 100x80x3 mm birch plywood test pieces were prepared for obtaining measurement data by laser cutting machine. The physical properties of the birch plywood used in the engraving process such as equilibrium moisture content, full dry density and air dry density are given in Table 1.

Table 1. Physical properties of birch plywood

Physical Properties		
Equilibrium Humidity (%)	Full dry density (gr/cm³)	Air dry density (gr/cm³)
12.48	0.460	0.487

Lasersoft software of Triumph Company was used for the laser machine in the processing of the parts. The laser machine cutting head distance on these parts was adjusted to 3, 4, 5, 6 and 7 mm. The laser machine cutting speed was applied at five different speeds of 100, 150, 200, 250 and 300 mm/sec and the power of the 150-watt tube was applied at 10%, 15%, 20%, 25% and 30%. With these processing parameters, the scraping height occurring in the material was measured and how much change in which parameter was determined. The milling parameters used are shown in Table 2 for power, speed and focal distance. Using the L25 orthogonal array, a Taguchi experimental design was applied to the data obtained from the tests to determine the effect of each independent input parameter on the dependent parameters. The independent variables are laser power 10 W - 30 W, engraving speed 100 mm/sec - 300 mm/sec, and focal distance 3 - 7 mm.

Table 2. Scraping parameters

Parameters		Power (%W)	Speed (mm/s)	Focus distance (mm)
		P	S	F
Symbol	1	10	100	3
	2	15	150	4
	3	20	200	5
	4	25	250	6
	5	30	300	7

The wood engraving process was carried out with a 3-axis industrial CO_2 laser machine with 150W power. The laser cutting machine where the engraving process was carried out is shown in Figure 1.

Figure 1. CO_2 laser machine used in the engraving process.

3. Results and Discussion

Plywood samples made of 3 mm birch (*Betula pendula*) wood were engraved with a CO_2 laser cutting device at different parameters. A total of 25 experiments were carried out to determine the scraping depth (D) values using Taguchi L25 orthogonal array. With the determined parameters, the milling process was carried out on the wood samples as shown in Figure 2.

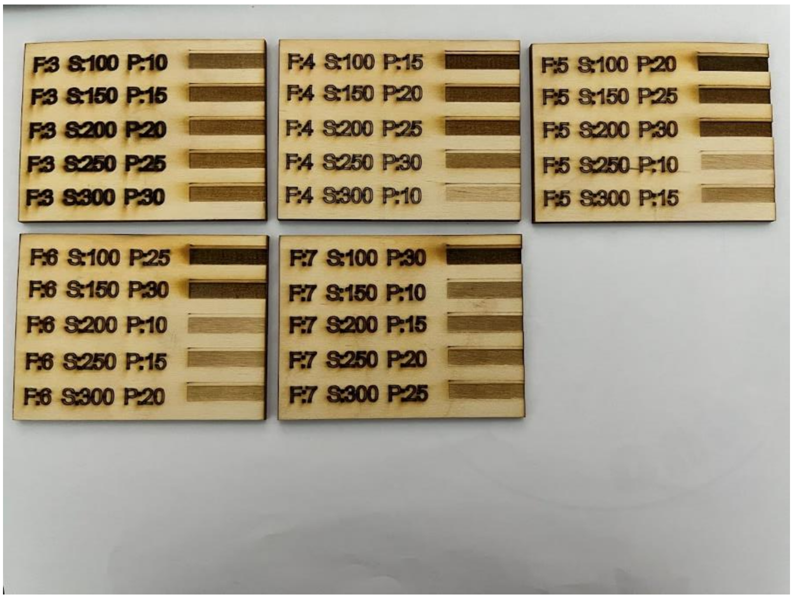

Figure 2. Processed birch plywood material.

Taguchi method was applied to determine the effect of all input parameters on the output parameters with the selected L25 orthogonal array. Preliminary engraving tests were performed to determine the range of input parameter values. For the 150 W laser, the power parameters were set between 10%-50%, 100-300 mm/s for the engraving speed and 3-7 mm for the laser head focal length.

A total of 25 engraving operations were performed to determine the engraving depth (D) values using Taguchi L25 orthogonal test setup. With the determined power, speed and focal height parameters, scraping was performed on plywood samples as shown in Figure 2 and analysed by connecting to the computer in the digital microscope shown in Figure 3.

Thanks to the 220X digital zoom feature, the microscope showed the scraping depth (D) and width in Figure 4. The images taken from the microscope were transferred to the computer and recorded from the appropriate parts of the samples by indicating the process dimensions on the image.

Figure 3. Digital microscope.

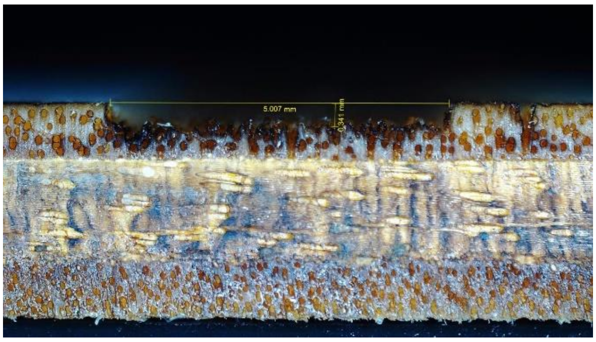

Figure 4. Wood plywood milling depth (D) and determined milling width.

Figure 5 shows the engraving process on wood birch plywood samples using a digital microscope. In order to measure the test results consistently on the samples, the engraving process was carried out with a width of 5 mm with a precision of 0.001. The experimental samples created with the L25 taguchi sequence and the measurement data obtained from these samples are shown in Table 3. Taguchi orthogonal L25 array ANOVA analysis of variance was performed to evaluate the basic parameters affecting the depth of scraping process on the wood plywood surface. The basic parameters and the most influential parameters were analysed using Taguchi-based SN ratio.

According to the results of ANOVA analysis of variance in Table 4, it is understood that firstly the laser power is the most effective parameter in the engraving depth process and then the engraving speed is the effective parameter. Since $P>0.05$, the focal length of the laser cutting head was found to have the least effect on the engraving depth.

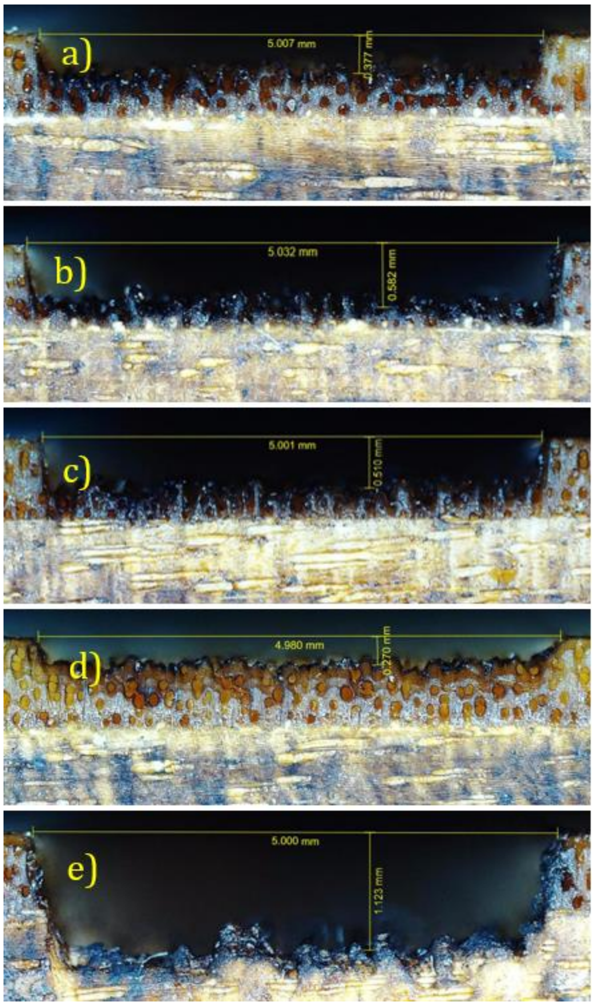

Figure 5. a) F:3-S:200-P:20, b) F:4-S:100-P:15, c) F:5-S:150-P:25, d) F:6-S:300-P:20, e) F:7-S:100-P:30.

Table 3. Measurement results obtained from the experimental study

Experiment No	Independent variable parameters			Dependent Variable
	P (%W)	S (mm/s)	F (mm)	Depth (mm) H
1	1	1	1	0.223
2	1	2	2	0.463
3	1	3	3	0.377
4	1	4	4	0.389
5	1	5	5	0.341
6	2	1	2	0.582
7	2	2	3	0.517
8	2	3	4	0.510
9	2	4	5	0.413
10	2	5	1	0.083
11	3	1	3	0.761
12	3	2	4	0.649
13	3	3	5	0.664
14	3	4	1	0.092
15	3	5	2	0.199
16	4	1	4	0.778
17	4	2	5	0.741
18	4	3	1	0.107
19	4	4	2	0.211
20	4	5	3	0.270
21	5	1	5	1.123
22	5	2	1	0.139
23	5	3	2	0.280
24	5	4	3	0.333
25	5	5	4	0.353

Table 4. ANOVA variance analysis results

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Focus	4	0.03580	2.25%	0.03	0.008	0.99	0.450
Speed	4	0.64557	40.56%	0.64	0.161	17.85	0.000
Power	4	0.80171	50.37%	0.801	0.200	22.17	0.000
Error	12	0.10848	6.82%	0.108	0.009		
Total	24	1.59156	100%				

3.1. Effect of process parameters on milling depth

When the analysis of variance in Table 5 and the Mean of S/N ratios in Figure 6 are analysed, it is understood that the laser head focal distance is not an effective parameter in the engraving depth. It was found that at low power and high speed, the engraving depth was low, while at high power and low processing speed, the engraving depth was high.

Table 5. Response table for signal-to-noise ratios

Level	Focus	Speed	Power
1	-9.148	-4.256	-18.386
2	-9.116	-7.183	-9.997
3	-8.886	-9.670	-7.500
4	-9.817	-11.934	-5.806
5	-9.157	-13.081	-4.436
Delta	0.930	8.825	13.950
Rank	3	2	1

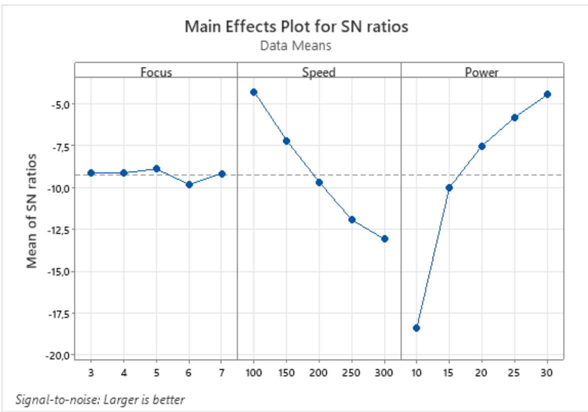

Figure 6. Effect of laser cutting parameters on the scraping depth (SN ratios).

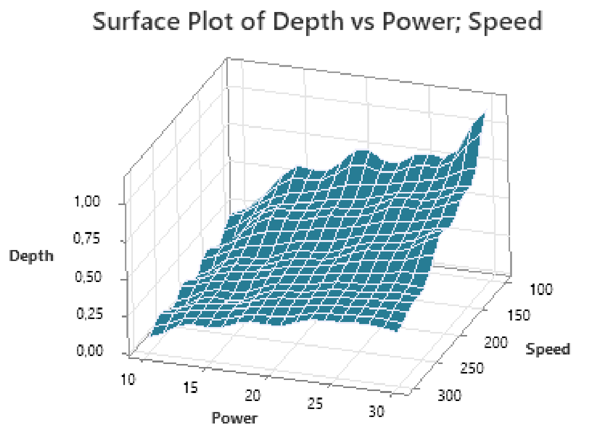

Figure 7. Graph of speed and power affecting milling depth (D).

According to the surface plot graph in Figure 7, when the laser power is increased and the feed rate is decreased, the depth of engraving increases. According to the graph, it is understood that the choice of high power and low speed has an increasing effect on the scraping depth. Low power and high speed should be preferred when the depth is desired to be at the minimum level.

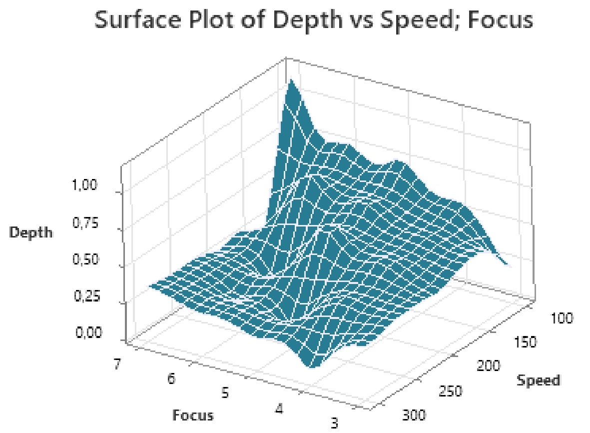

Figure 8. Focus and velocity graph affecting the scraping depth (D).

When the surface plot graph in Figure 8 is analysed, it can be seen that when the focal height is partially increased and the feed rate is decreased, the milling depth increases. According to the graph, it is understood that the average focal height and low-speed preference affect the milling depth in an increasing direction. It is understood that low focal length and high speed should be preferred when the depth is desired to be at the minimum level.

When the surface plot graph in Figure 9 is analysed, it shows similar changes to Figure 8. When the laser power and focal height are increased, the engraving depth increases. According to the graph, it is understood that high power and focal height have an increasing effect on the engraving depth. Low power should be preferred when the depth is desired to be at the minimum level.

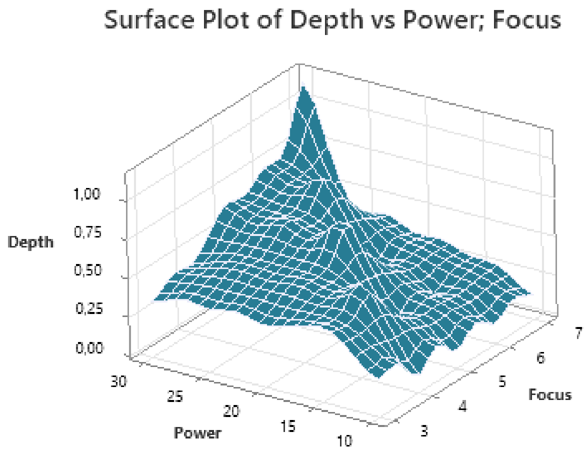

Figure 9. Graph of speed and power affecting milling depth (D).

According to the L25 Taguchi octogonal array highest is best S/N optimisation results, and the highest optimisation scraping result according to F:5, S:100, P:30 data is given in Figure 10 (a). The example of the lowest optimisation according to F:6, S:300, and P:10 data is also shown in Figure 10 (b).

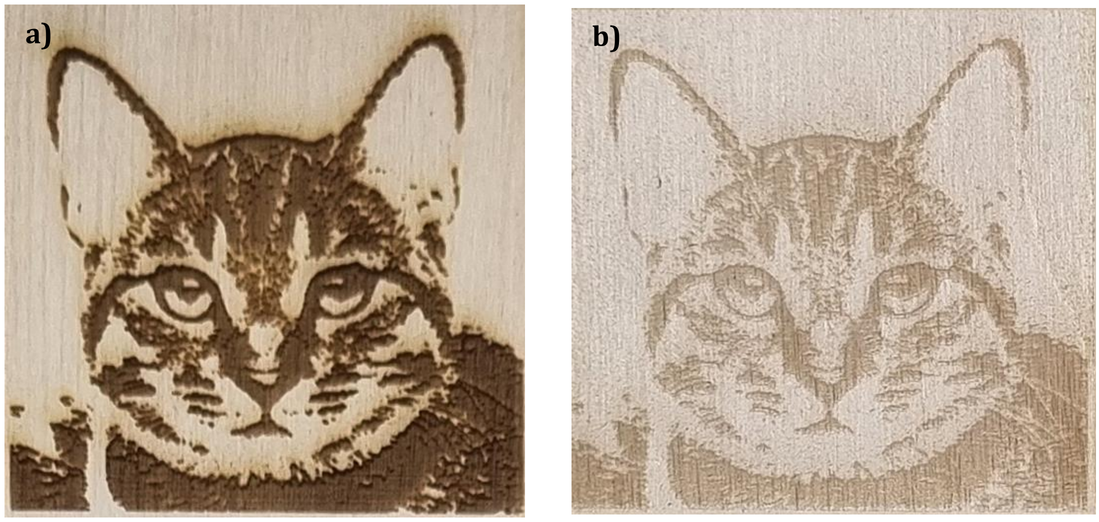

Figure 10. Highest optimised milling result.

4. Conclusions

There are many parameters affecting the engraving quality in wood laser engraving processes. The most effective of these parameters are the focal length of the laser head to the material, laser cutting speed and laser engraving power. In this study, the effect of which of the factors affecting the engraving quality of the glass tube CO_2 laser cutting device with 150 W power on the engraving quality was investigated and carried out experimentally. In order to reduce the number of experiments, the optimisation process was performed using the L25 Taguchi orthogonal array. ANOVA analysis of variance was performed on the S/N data and it was determined that the most effective parameters were laser engraving speed and laser power. It was found that the focal length of the laser head to the material was not an effective factor compared to other parameters. Among the parameters used in the engraving process on wood birch plywood, it has been determined by experimental studies that low engraving speed and high engraving power give the best result and high speed and low power give the lowest engraving result. In addition, it was determined that more aesthetic images were created by increasing the scraping depth.

Author Contributions

The percentage of the author(s) contributions is presented below. All authors reviewed and approved the final version of the manuscript.

	M.G.	Ç.E.
D	70	30
S	50	50
DCP	70	30
DAI	60	40
L	40	60
W	50	50
SR	60	40

D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, SR= submission and revision.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Approval Statement

Since no studies were conducted on animals or humans in this study, ethics committee approval was not received.

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