



Kinetic Analysis of The Jameson Flotation Cell's Performance in Ultra-Clean Fine Coal Beneficiation

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Graphical/Tabular Abstract (Grafik Özet)

The performance of the Jameson flotation cell in the beneficiation of ultra-clean bituminous coal was evaluated using combustible recovery and flotation rate constant under different operating conditions / Ultra temiz bitümlü kömürün zenginleştirilmesinde Jameson flotasyon hücresinin performansı, farklı işletme koşulları altında yanabilir kısım verimi ve flotasyon hız sabiti kullanılarak değerlendirilmiştir.

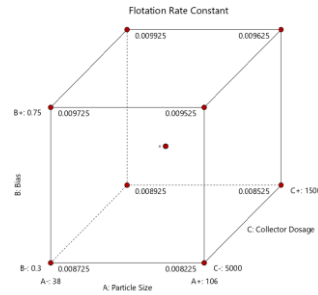


Figure A: Cube Graph / Şekil A: Küp grafiği

Highlights (Önemli noktalar)

- The performance of the Jameson flotation cell was evaluated and optimized for ultra-clean bituminous coal beneficiation / Jameson flotasyon hücresinin performansı, ultra temiz bitümlü kömür zenginleştirme işlemi için değerlendirilmiş ve optimize edilmiştir.
- The effects of frother dosage, bias rate, and particle size on combustible recovery and flotation rate constant were investigated / Köpürtücü dozajı, sapma oranı ve tane boyutunun yanabilir kısım verimi ve flotasyon hız sabiti üzerindeki etkileri incelenmiştir.
- The Jameson flotation cell exhibited high separation performance, particularly for fine particle sizes / Jameson flotasyon hücresi, özellikle ince tane boyutlarında yüksek ayırma performansı sergilemiştir.

Aim (Amaç): To evaluate and optimize the performance of the Jameson flotation cell in the beneficiation of ultra-clean bituminous coal by investigating the effects of frother dosage, bias rate, and particle size on combustible recovery and flotation rate constant / Köpürtücü dozajı, bias oranı ve tane boyutunun yanabilir kısım verimi ve flotasyon hız sabiti üzerindeki etkilerini inceleyerek, ultra temiz bitümlü kömürün zenginleştirilmesinde Jameson flotasyon hücresinin performansını değerlendirmek ve optimize etmek.

Originality (Özgünlük): This study presents a comprehensive evaluation of the Jameson flotation cell by combining combustible recovery and flotation rate constant to assess flotation performance under different operating conditions / Bu çalışma, farklı işletme koşulları altındaki flotasyon performansını değerlendirmek amacıyla yanabilir kısım verimi ve flotasyon hız sabitini birleştirerek Jameson flotasyon hücresinin kapsamlı bir değerlendirmesini sunmaktadır.

Results (Bulgular): The experimental results showed that the Jameson flotation cell achieved high combustible recovery and flotation rate constants, especially at fine particle sizes / Deneyisel sonuçlar, Jameson flotasyon hücresinin özellikle ince tane boyutlarında yüksek yanabilir kısım verimi ve yüksek flotasyon hız sabitleri elde ettiğini göstermiştir

Conclusion (Sonuç): The Jameson flotation cell is an effective flotation system for the beneficiation of ultra-clean bituminous coal, providing high combustible recovery and flotation rate constants under appropriate operating conditions / Jameson flotasyon hücresi, ultra temiz bitümlü kömürün zenginleştirilmesinde etkili bir flotasyon sistemi olup, uygun işletme koşulları altında yüksek yanabilir kısım verimi ve yüksek flotasyon hız sabitleri sağlamaktadır.



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Abstract

This study evaluates and optimizes the Jameson flotation cell's performance in the ultra-clean bituminous coal's beneficiation. The experimental design considered three key parameters: frother dosage (15 ppm), bias rate (0,75 cm/s), and a fixed particle size (38 µm). These variables effects on combustible recovery (CR, %) and the flotation rate constant (k), which represents flotation kinetics, were analyzed. Experimental results demonstrate that the Jameson cell achieves high efficiency and rapid flotation kinetics, particularly at fine particle sizes. Additionally, it was observed that the applied bias and frother dosage significantly influence foam stability and bubble-particle interactions, thereby shaping the overall performance.

Ultra Temiz İnce Kömür Zenginleştirme İşleminde Jameson Flotasyon Hücresinin Performansının Kinetik Analizi

Makale Bilgisi

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Öz

Bu çalışma, ultra temiz bitümlü kömürün zenginleştirilmesinde Jameson flotasyon hücresinin performansını değerlendirmekte ve optimize etmektedir. Deneyel tasarımda üç temel parametre dikkate alınmıştır: köpürtücü dozajı (15 ppm), bias hızı (0,75 cm/s) ve sabit partikül boyutu (38 µm). Bu değişkenlerin yanabilir kısım verimi (CR, %) ve flotasyon kinetiğini temsil eden flotasyon hızı sabiti (k) üzerindeki etkileri analiz edilmiştir. Deneyel sonuçlar, Jameson hücresinin özellikle ince partikül boyutlarında yüksek verimlilik ve hızlı flotasyon kinetiği sağladığını göstermektedir. Ek olarak, uygulanan bias ve köpürtücü dozajının köpük stabilitesini ve kabarcık-partikül etkileşimlerini önemli ölçüde etkilediği ve böylece genel performansı şekillendirdiği gözlemlenmiştir.

1. INTRODUCTION (GİRİŞ)

As global energy demand continues to rise, coal has long been a primary energy source, with vast reserves still available, and its storage capacity is being expanded today. However, the increasing intensity of coal use, driven by rapidly growing energy consumption, poses serious threats to human health. Therefore, technologies that minimize ash, recover fine coal particles, and reduce waste are crucial for environmental sustainability. These capabilities include flocculation, hydrophobic flocculation, oil agglomeration, and flotation, widely and effectively used in coal separation and enrichment processes [1]. Flotation is one of the most effective methods in fine coal beneficiation for separating valuable coal fractions from ash and

other gangue minerals. This separation relies on the principle that hydrophobic coal particles attach to air bubbles, thereby separating from hydrophilic minerals. Establishing this fundamental principle highlights the critical impact of surface properties on flotation efficiency and elucidates the role of surface chemistry in selective separation [2].

The Jameson cell is an innovative flotation technology combining air and pulp in a vertical tube. In this system, the air-pulp mixture is distributed into a dense froth bed formed by fine bubbles, creating a favorable environment for hydrophobic particles to collide with and attach to the bubbles [3, 4]. The primary advantages of the Jameson cell include its ability to collect particles in a downward-flowing fluid rapidly and its compact

design, which offers space efficiency. Additionally, the cell's self-aspiration capability eliminates the need for external air supply equipment, such as compressors or blowers, thereby reducing operating costs and maintaining a simple structure [3, 5]. The design of the Jameson cell leverages advancements in single-bubble dynamics and the hydrodynamics of two-phase flows. A plunging jet generates controlled microbubbles, creating a large surface area that maximizes collection efficiency in the downward flow. The downward flow velocity is optimized to transport bubbles while being low enough to allow bubbles to rise against the flow, forming a high gas-content mixture. The flow diameter and pulp flow rate are carefully matched to ensure the transport of large particles [6]. The Jameson cell's simple geometry utilizes the plunging jet's hydrodynamic characteristics to achieve effective bubble-particle contact. The high-velocity flow in the downcomer induces air self-aspiration, while the large area in the main cell optimizes the rise velocity of the bubbles [7]. Industrial applications report that the Jameson cell achieves mineral recovery rates exceeding 90%, attributed to its enhanced bubble-particle collision efficiency. This high efficiency is directly linked to the cell's characteristic design, where microbubbles formed by liquid jets facilitate frequent and effective collisions with particles, accelerating flotation kinetics [8]. Optimizing microbubble production mechanisms enhances energy efficiency, particularly in fine coal flotation, yielding successful results. Automatic optimization of parameters such as air velocity, froth level, and liquid feed can further improve performance, aligning with modern mineral processing needs [9, 10]. Wash water reduces gangue content, improving separation quality and the purity of valuable minerals. However, excessive wash water can negatively impact target mineral recovery. When optimized adequately for froth conditions, wash water increases concentrate grade without compromising recovery. Different frother types influence froth stability [11, 12]. The cell's high efficiency and success in recovering fine-grained minerals are widely documented, with findings supporting its effectiveness in separating low-ash coal through flotation [13]. The natural hydrophobicity of coal surfaces and the role of frother in optimizing surface interactions are noteworthy [14]. In this study, particle size, bias (wash water flow), and frother dosage were selected as fixed parameters, and their optimum values were determined to comprehensively examine their effects on flotation yield and the flotation rate constant (k). The contribution of each parameter to

flotation performance was systematically evaluated within the framework of the experimental design, and the obtained results provide practical recommendations for the performance of the Jameson cell in fine coal beneficiation. To evaluate the effects of fixed variables (particle size, bias velocity/air flow rate, and frother dosage) on combustible recovery and flotation kinetics, experiments were conducted using a 2³ full factorial experimental design. A total of 12 experiments were performed for Jameson flotation machine. Eight of these experiments were conducted at low and high levels, and four at medium levels, using the independent variables (particle size, bias velocity, and frother dosage).

2. MATERIALS AND METHODS (MATERIAL VE METOD)

2.1. Experimental Equipment (Deneyisel Ekipman)

A coal sample with a particle size of 0.5-18 mm, obtained from the Kozlu operation of the Turkish Hard Coal Enterprise (THCE), was homogenized under laboratory conditions. The chemical analysis of the coal sample is presented in Table 1 below.

Table 1. Analysis of the coal sample (Kömür örneği analizi)

Analysis	Air-Dry Basis
Moisture (%)	1.61
Ash (%)	4.75
Calorific Value (Kcal/kg)	7996,1

Subsequently, the sample volume was systematically reduced using the coning and quartering method and subjected to crushing and screening processes under appropriate conditions, with particle sizes determined. Cytec's polyglycol-based Aero froth 65 (AF-65), which enhances foam formation and facilitates the adhesion of fine coal particles to the surface, was selected as a frother.

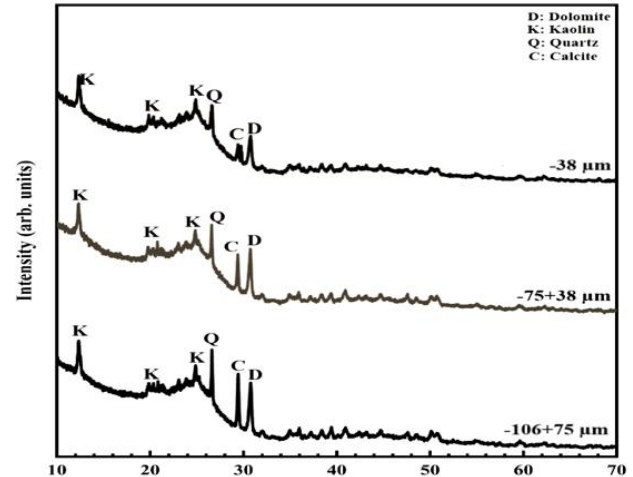


Figure 1. XRD results for ultra-clean coal (Ultra temiz kömür için XRD sonuçları)

Tap water was used to standardize the process conditions and ensure the reproducibility of experiments because it is a commonly used resource in industrial applications. The XRD graph has been plotted and interpreted in Figure 1.

XRD analysis results reveal that the mineral distribution varies across different particle size fractions of the same sample. Due to its low hardness and structural properties, kaolinite tends to break down more easily during grinding and is therefore concentrated in the $-38\ \mu\text{m}$ fraction. In contrast, quartz is more resistant to grinding because of its hard and durable nature, making it more dominant in coarser fractions, especially in the $-106+75\ \mu\text{m}$ range. Calcite and dolomite are generally more prominent in the medium and coarse fractions but are present in smaller amounts in the finer fraction. This distribution indicates that grinding behavior varies depending on the physical properties of the minerals.

2.2. Experimental Design (Deney Tasarımı)

In the Jameson flotation cell, the parameters of particle size (μm), frother dosage (ppm) and bias (cm/s) were investigated as variables and a systematic evaluation was conducted according to the established experimental design. The experimental conditions are given in Table 2.

Table 2. Experimental conditions (Deney koşulları)

Experiment No.	Particle size (μm)	Bias (cm/s)	Frother Dosage (ppm)
1.	-38	0.75	5
2.	-38	0.75	15
3.	-106+75	0.75	5
4.	-106+75	0.75	15
5.	-75+38	0.525	10
6.	-75+38	0.525	10
7.	-75+38	0.525	10
8.	-75+38	0.525	10
9.	-38	0.3	5
10.	-38	0.3	15
11.	-106+75	0.3	5
12.	-106+75	0.3	15

Experiments were initiated according to the specified conditions. Initially, while the tailings and wash water flow rates were kept constant, the feed flow rate was controlled to adjust the bias ratio. The tank was filled with 80 liters of tap water, and Cytec Aero froth 65 frother was added in amounts specified by the experimental design. The frother-

containing water was circulated and returned to the same tank until the system reached equilibrium. A 5% solids ratio coal sample was transferred to the conditioning tank and homogenized into a uniform pulp. This pulp was then fed under high pressure to the vertical tube of the Jameson cell, enabling the production of fine bubbles and the collection of coal particles through the plunging jet mechanism. Throughout the flotation process, the tailings flow was redirected to the conditioning tank to maintain system continuity, while the concentrate was collected at predetermined time intervals (60, 90, 150, 300 seconds). After the sample in the conditioning tank was fully depleted, the material remaining in the cell was separated as tailings. The samples collected at the specified intervals were filtered, dried, and precisely weighed. This detailed approach not only enhanced the accuracy of the experimental data but also provided a robust foundation for analyzing the effectiveness of the Jameson cell in coal beneficiation. A schematical illustration of Jameson flotation cell was given in Figure 2.



Figure 2. Jameson flotation cell (Jameson flotasyon hücresi)

Based on experimental data, Analysis of Variance (ANOVA) is widely used to statistically evaluate the effects of independent variables on the dependent variable, interactions between variables, and the significance of the model. In addition to testing the suitability of the regression model, ANOVA also reveals systematic errors and statistical significance [15, 16]. Particularly in multivariate engineering systems such as mineral processing and flotation, models developed through ANOVA and regression analyses provide effective and reliable results for process optimization [17]

$$Y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1}^k \beta_{ij} x_i^2 + \sum \sum_{i < j} \beta_{ij} x_i x_j + \varepsilon$$

here, y is the dependent parameter, β represents the regression coefficients, and x denotes the independent parameters.

Response Surface Methodology (RSM) is a collection of statistical and mathematical modeling techniques used when multiple independent variables influence one or more responses. This method is particularly employed in optimizing complex processes, understanding system behavior, and evaluating interactions between factors [14]. By utilizing statistical tools such as the Design of

Experiments (DOE), regression analysis, and the generation of response surface curves, RSM enables the construction of a mathematical model of the system, allowing prediction of how the response varies concerning the factors. As such, it is a powerful optimization tool preferred in multivariate engineering applications, including mineral processing, flotation, and chemical processes [18, 19].

3. RESULTS (BULGULAR)

The results obtained from the flotation tests are given in Table 3 and the conditions (The experimental conditions with the highest k and R^2 values were taken as optimal) are given in Table 4.

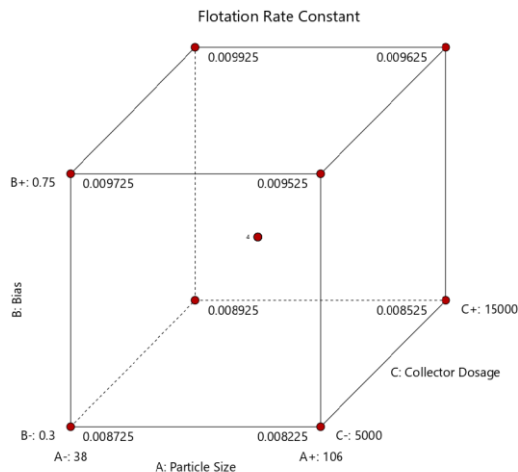
Table 3. Conditions (Koşullar)

Particle Size (μm)	-38
Frother Dosage (ppm)	15
Bias (cm/s)	0.75
CR (%)	93
Flotation Rate Constant (k, s^{-1})	0.0099
R^2	0.9980

Table 4. Experimental results (Deney sonuçları)

Experiments No.	Particle Size (μm)	Frother Dosage (ppm)	Bias (cm/s)	Flotation Rate Constant (k, s^{-1})	R^2	CR, %
1	-38	5	0.75	0.0097	0.9979	92.65
2	-38	15	0.75	0.0099	0.9980	93.00
3	-106+75	5	0.75	0.0095	0.9976	92.24
4	-106+75	15	0.75	0.0096	0.9976	92.49
5	-75+38	10	0.525	0.0094	0.9972	91.98
6	-75+38	10	0.525	0.0093	0.9969	91.96
7	-75+38	10	0.525	0.0094	0.9970	91.97
8	-75+38	10	0.525	0.0094	0.9970	91.96
9	-38	5	0.3	0.0087	0.9926	90.45
10	-38	15	0.3	0.0089	0.9939	90.89
11	-106+75	5	0.3	0.0082	0.9889	89.10
12	-106+75	15	0.3	0.0085	0.9908	90.04

Figure 3 visualizes the effects of particle size (A: ranging from 38–106 μm), bias (B: ranging from 0.3–0.75 cm/s), and frother dosage (C: ranging from 5–15 ppm) on the flotation rate constant (k : ranging from 0.008225–0.009925). The k values are indicated at each corner, with a red dot at the center representing the average of the experimental conditions. As particle size increases from 38 μm to 106 μm , a general decrease in the k value is observed [20]. As bias increases from 0.3 cm/s to 0.75 cm/s, a significant increase in the k value is noted [21]. As the frother dosage increases from 5 ppm to 15 ppm, the k value generally increases. Low particle size and high bias enhance the k value, while the effect of frother dosage is limited [22]. This confirms that the Jameson flotation cell operates effectively with fine particles and optimized bias.

**Figure 3.** Cube graph (Küp grafiği)

The flotation rate constant (typically denoted as k) is a fundamental parameter of flotation kinetics, representing the rate at which mineral particles attach to bubbles during the flotation process. In calculating the flotation rate constant, the first-order kinetic model is commonly used, and the relationship between recovery (R) and time (t) is expressed as follows:

Kinetic Model Formula:

$$R = 1 - e^{-kt}$$

Here, k represents the flotation rate constant. Based on experimental data, the value of $1-R$ is calculated from recovery values measured at different times, and its natural logarithm ($\ln(1-R)$) is plotted against flotation time. If a linear relationship is observed, the absolute value of the slope corresponds to the k constant. This kinetic approach is widely used to evaluate flotation processes, enabling quantitative comparison of process performance [23]. Experimentally, recovery (R) values are measured at different time intervals.

Subsequently, linear regression is performed using the following transformation:

$$\ln(1-R) = -kt$$

A linear form is thus obtained. As a result of this transformation, the expression $\ln(1-R)$ is plotted on the y-axis, while time (t) is placed on the x-axis. In this linear equation, the slope corresponds to $-k$, and the absolute value of the regression line's slope is accepted as the flotation rate constant. This method

provides a reliable basis for quantitatively comparing flotation systems' performance and conducting optimization studies [24].

Initially, recovery values (R) at different flotation times are determined. Then, for each time point, the value of $1-R$ is calculated, and the natural logarithm ($\ln$) of these values is taken. The obtained $\ln(1-R)$ values are plotted against the corresponding flotation times. If the graph exhibits a linear relationship, the slope is calculated using linear regression. The rate constant (k) is defined as the absolute value of this linear slope. The obtained flotation rate constant ($k = 0.0099 \text{ s}^{-1}$) demonstrates that the Jameson cell facilitates rapid and effective bubble-particle interaction. Analysis of the hydrodynamic structure of the Jameson cell indicates that high-speed particle-bubble attachment occurs despite the short contact time [25]. The R^2 value of 0.9980 for the kinetic model, which is remarkably high, indicates an excellent fit of the experimental data to the kinetic model. Studies highlighting the effects of bubble size and cell design on model fit in the flotation of fine coal particles further support this finding [26]. As shown in Figure 4, the slope typically takes a negative value.

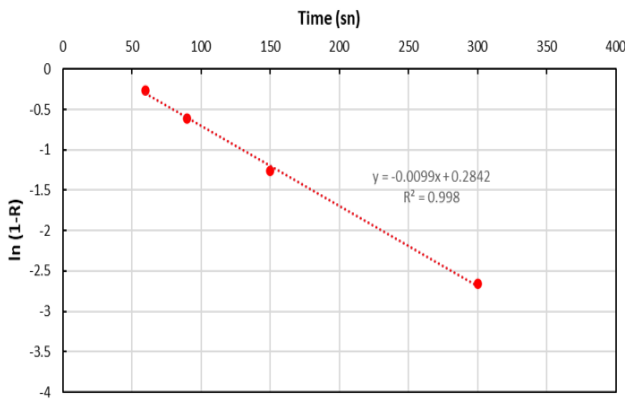


Figure 4. Flotation rate constant graph for optimum condition data (Optimum koşullar için flotasyon hızı sabiti grafiği)

In coal flotation, combustible matter (the valuable portion, typically the organic part of coal) is separated from ash and other gangue minerals. The **combustible efficiency (CR, %)** indicates the percentage of combustible parts in the feed that is recovered in the concentrate. This is calculated using a logic similar to flotation efficiency, but it takes ash content into account.

$$\%, CR = \left(\frac{A \times (100 - a_{\text{ash}})}{F \times (100 - f_{\text{ash}})} \right) \times 100$$

here, A and F represent the weights of the concentrate and the feed respectively while a_{ash} and f_{ash} denote the ash contents of the concentrate and the feed, respectively. The Combustible efficiency graph for the optimum values determined from the experimental results is presented in Figure 5.

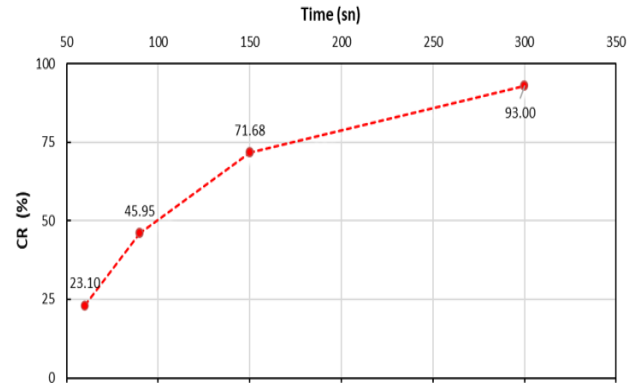


Figure 5. Combustible efficiency graph for optimum condition data (Optimum koşullar için yanıcı verimlilik grafiği)

4. CONCLUSIONS (SONUÇLAR)

For coal particles sized $38 \mu\text{m}$, a high recovery rate of 98.96% was achieved, demonstrating the effectiveness of the Jameson cell, particularly in the beneficiation of fine-grained coal. A low frother dosage (15 ppm) indicates that the Jameson cell has an energy- and reagent-efficient design. Setting the bias rate at 0.75 cm/s positively impacts particle separation. The obtained flotation rate constant ($K = 0.0099 \text{ s}^{-1}$) indicates rapid and effective bubble-particle interaction in the Jameson cell. The R^2 value of 0.9980 for the kinetic model had indicated a high level of agreement between the experimental data and the model. These findings demonstrate that the Jameson cell achieves successful results in the flotation of fine coal fractions, with both high efficiency and model fit. Experiments conducted in the Jameson flotation cell show that combining fine particle sizes, optimized frother dosages, and appropriate bias rates can significantly improve flotation efficiency and the kinetic rate constant. These parameters balanced and systematic optimization is critically important for process efficiency and economic considerations.

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DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

Güldane NACAK: She conducted the experiments, performed data analysis, prepared the visualizations, and wrote the original draft of the manuscript.

Deneyleri yürütmüş, verileri analiz etmiş, görselleştirmeleri hazırlamış ve makalenin ilk taslağını yazmıştır.

Selma DÜZYOL: She supervised the research, contributed to the study design and methodology, interpreted the results, critically reviewed the manuscript, and approved the final version.

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CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

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