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CLIMATIC SUITABILITY ANALYSIS AND EVALUATION OF POMOLOGICAL CHARACTERISTICS FOR WALNUT (*Juglans regia* L.) CULTIVATION IN KIRSEHIR PROVINCE

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Abstract: This study was conducted within the boundaries of Kırşehir Province, located between 38°50'–39°50' north latitude and 33°30'–34°50' east longitude. The research material consisted of the climatic and topographic parameters of Kırşehir and its districts, as well as walnut samples collected from these regions. Climatic factors considered included annual total precipitation, minimum temperature, number of days with temperatures below 5°C, relative humidity in spring and summer, number of days with temperatures exceeding 30°C, and wind speed. Climatic data covering the period between 2013 and 2023 were obtained from the Kırşehir Provincial Meteorological Directorate. Data from eight meteorological stations located in Akçakent, Akpınar, Boztepe (Malya), Çiçekdağı, Çiçekdağı TİGEM, Kaman, Kırşehir, and Mucur were used in the analysis. The spatial distribution of climatic parameters was modeled using the Inverse Distance Weighting (IDW) interpolation method in ArcGIS Pro 3.2. Topographic features such as slope and aspect were derived from a 25 m spatial resolution Digital Elevation Model (DEM) obtained via the Earth Explorer (USGS) platform. All climatic and topographic layers were weighted according to the Analytical Hierarchy Process (AHP), and a Weighted Overlay Analysis was performed to generate the climatic suitability map for walnut cultivation. In addition, walnut samples were collected from selected representative orchards across all districts for pomological evaluation. Pomological traits such as nut weight, kernel ratio, and shell thickness were measured using a digital caliper and a precision balance on 30 nut samples to assess the pomological properties of local genotypes and support the regional walnut production potential. According to the results, the most suitable areas for walnut cultivation are concentrated in the northwestern part of Kaman District, particularly around the Hirfanlı Dam, and in the northeastern parts of Çiçekdağı and Boztepe districts. The highest nut and kernel weights were recorded in Kaman and Çiçekdağı districts ($P < 0.05$).

Keywords: Kırşehir, Walnut cultivation, Climatic suitability, AHP, Weighted Overlay Analysis, Pomological characteristics

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1. Introduction

Walnut (*Juglans regia* L.) belongs to the class *Dicotyledoneae*, order *Juglandales*, family *Juglandaceae,* and genus *Juglans.* Today, there are approximately 22 recognized walnut species within the genus *Juglans*. Commonly known as the Anatolian or English walnut, *Juglans regia* L. is considered the most well-known among these species due to its distinct characteristics (Şen, 2011). Walnut cultivars grown worldwide for nut production hold significant potential for cultivation in Türkiye.

When planning fruit cultivation in a region, it is essential to determine the most suitable variety and genotype for that specific area. To identify the most appropriate variety and species, the natural flora of the region must be taken into account; otherwise, various problems related to productivity and quality may arise. For a fruit tree to grow in any ecological zone, produce high-quality fruits, and successfully ripen its yield, climatic and soil factors are of vital importance. Therefore, climate is the most decisive factor in selecting appropriate varieties and species for a given region. Among various climatic parameters affecting fruit cultivation, temperature is the most critical, as plants require specific combinations of low and high temperatures during their vegetative periods (Özbek, 1975; Bükücü and Sütyemez, 2016).

Soil and climate characteristics are highly important for determining suitable areas for agricultural production. In identifying areas suitable for the cultivation of each crop, in addition to soil and climate factors, the landform must also be considered (Yıldırım, 2002). Consequently, independent variables such as climate, aspect, slope, and geographic location can be analyzed and modeled within a GIS environment. Geographic Information Systems (GIS) and remote sensing data are widely used for land suitability assessment. GIS serves as a tool to develop alternative uses of agricultural land, precision farming, and land suitability mapping (Amiri et al., 2012). Multiple databases, including climate, soil, and vegetation information, are utilized in determining land suitability (Akıncı et al., 2013; Karimi et al., 2018). In addition to modern technologies such as GIS and remote sensing, Multi-Criteria Decision-Making (MCDM) methods particularly the Analytic Hierarchy Process (AHP) are frequently applied to integrate and evaluate different spatial parameters. AHP, developed by Thomas Saaty, is a mathematical approach commonly used to determine the relative weights of evaluation criteria (Saaty, 1990). For the sustainable and rational use of land, land characteristics should be well understood. Effective management of land resources requires their utilization according to suitability levels (Karas et al., 2017).

MCDM methods are highly useful tools in agricultural land-use and site selection studies, as they facilitate suitable site selection, ensure sustainability, preventing degradation, and restoring ecology (Sarkar et al., 2021). The primary goal of land-use planning is to protect natural resources and ecosystem services for present and future generations while supporting decision-makers and land users in selecting and implementing optimal land-use practices (Bunning and De Pauw, 2017; Karas, 2020). The AHP method is used successfully in land evaluation studies and yields quite successful outcomes when integrated with geographical information systems (GIS) (Pilevar et al., 2020; Amini et al., 2020).

While agricultural land suitability assessments for macro-regions were prominent in the past, crop-specific suitability analyses have gained increasing importance in recent years (Sharma et al., 2018; Everest et al., 2021). In this study, the Analytic Hierarchy Process (AHP), a GIS-based Multi-Criteria Decision Analysis (MCDA) method, was applied to determine suitable areas for walnut cultivation based on climatic and topographic factors. Additionally, during the harvest period, walnut samples were collected from representative orchards designated and guided by the Kırşehir District Directorates of Agriculture. The samples were obtained from standard orchards managed by growers who applied uniform cultivation practices and had trees of the same age, in order to ensure consistency in pomological evaluation.

2. Materials and Methods

This study was conducted to determine suitable areas for walnut cultivation in Kırşehir Province by evaluating climatic and topographic factors using the Analytic Hierarchy Process (AHP) method. The administrative boundaries of the province and its districts were obtained from the GADM (Anonymous, 2023a) database.

Climatic data covering the period 2013–2023 were provided by the Kırşehir Provincial Directorate of Meteorology. Observations were obtained from eight meteorological stations: Akçakent, Akpınar, Boztepe (Malya), Çiçekdağı, Çiçekdağı TİGEM, Kaman, Kırşehir, and Mucur (Anonymous, 2023b). The following climatic parameters were analyzed:

- Minimum temperature (March–May)
- Number of days below 5 °C (March–May)
- Number of days above 30 °C (July–August)
- Annual total precipitation
- Wind speed (March–May)
- Spring relative humidity (March–May)
- Summer relative humidity (July–August)

Point-based climatic data were converted into raster format using the Inverse Distance Weighted (IDW) interpolation method. One of the most frequently used deterministic models in spatial interpolation is the inverse-distance weighting (IDW) method. The Inverse Distance Weighted (IDW) method is a commonly used deterministic interpolation technique that estimates values at unsampled locations as a weighted average of nearby measured points (Lu and Wong, 2008). Slope and aspect were derived from the USGS Digital Elevation Model (DEM) with a 25 m spatial resolution (Anonymous, 2023c). All datasets were projected to a common coordinate system (UTM Zone 36N, WGS 84). Nine environmental criteria were used for the suitability analysis, including seven climatic parameters and two topographic parameters. Pairwise comparisons were performed using a 1–9 scale (Saaty, 1980), allowing intermediate values for moderate differences in importance. In the AHP method, evaluating consistency is important for measuring the reliability of decisions. For this purpose, the Consistency Index (CI) is calculated (Zhou and Shi, 2009). Normalized weights were calculated, and the Consistency Ratio (CR) was checked to ensure matrix consistency (CR<0.10). All spatial analyses and raster operations were performed in ArcGIS Pro 3.2 (Anonymous, 2022). Using the criterion weights determined by the AHP method, a suitability map for walnut cultivation was generated through Weighted Overlay Analysis. To validate the suitability map, 210 walnut fruit samples were collected from representative orchards identified under the guidance of the Kırşehir District Directorates of Agriculture in seven districts (Akçakent, Akpınar, Boztepe, Çiçekdağı, Kaman, Merkez, and Mucur), with 30 samples obtained from each district. Pomological characteristics, including nut width, nut length, shell thickness, kernel weight, and kernel ratio, were measured. Nut dimensions were recorded using a digital caliper with 0.01 mm precision, and weights were determined using a precision balance with an accuracy of 0.01 g. Based on these measurements, the kernel ratio was calculated as the percentage of kernel weight to total nut weight (Şen, 1980).

The collected data were analyzed using ANOVA, and significant differences among districts were determined with the Tukey HSD test (P<0.05) (Anonymous, 2000).

3. Results and Discussion

The Analytic Hierarchy Process (AHP) analysis produced consistent results (CR = 0.063 <0.10), confirming the reliability of the decision matrix. Among the evaluated criteria, aspect had the highest relative importance weight (0.345), indicating that sun exposure and microclimatic effects are decisive factors influencing walnut cultivation in Kırşehir Province. This was followed by minimum temperature (0.230), number of days below 5 °C (0.152), and slope (0.100). Other parameters, including number of days above 30 °C, precipitation, wind speed, and relative humidity, received lower weights and were considered as supportive climatic factors contributing to overall suitability (Table 1). When the Weighted Overlay Analysis was performed using these weights, the resulting suitability map classified the study area into four FAO land suitability classes: S1 (Highly suitable), S2 (Moderately suitable), S3 (Marginally suitable), and N (Not suitable). Final suitability classes were defined according to (Anonymous, 1976). Field verification results supported the spatial analysis findings. Most sampled walnut orchards were located within areas classified as moderately suitable (S2) or marginally suitable (S3). The geographic coordinates of each orchard were overlaid on the suitability map to confirm their spatial correspondence with the predicted suitability classes.

Table 1. Criteria and their weights determined by the AHP method

Criteria	Weight (%)
Aspect	34.5
Minimum Temperature	23.0
Number or Days Bellow 5°C	15.2
Slope	10.0
Number or Days Above30°C	4.6
Precipitation	3.4
Wing	3.1
Spiring Relative Humidity	3.1
Summer Relative Humidity	3.1

Pomological evaluations of the collected walnut samples revealed significant variations among districts. The measured traits included nut width, nut length, shell thickness, and kernel weight. Based on these measurements, the kernel ratio (%) was calculated as the proportion of kernel weight / nut weight × 100. Analysis of variance (ANOVA) indicated statistically significant differences among districts ($P<0.05$). Overall, orchards located in areas classified as moderately suitable (S2) exhibited higher kernel weigth characteristic compared to those in marginally suitable (S3) areas. Walnuts generally achieve their largest size and highest yield along river corridors and on lower slopes facing north or east (Ponder, 2004). The aspect of the site directly influences production success. Particularly in Central Anatolia, where late spring frosts are frequent, north-facing slopes delay flowering in early-budding walnut varieties, thereby protecting them from frost damage (Atmaca and Cüce, 2023). In this study, aspect was identified as the most influential criterion, with northwestern and northeastern slopes providing the most favorable microclimatic conditions for walnut cultivation.

Ecological studies on *Juglans* species native to North America have demonstrated that the growth rhythm of woody plants is closely related to both active (+10 °C) and effective (+5 °C) cumulative temperatures. Shoot elongation in all species predominantly occurs in May–June, slows in July, and ceases in August. During bud swelling, flowering, and fruit set stages, cumulative temperatures above +5 °C were recorded (Ishchuk et al., 2021).

Late spring frosts (temperatures dropping to around –3 °C) occurring in late April or early May can damage young shoots and apical buds, resulting in significant yield losses (Verma, 2014). Therefore, minimum temperature was considered a key climatic parameter in this study to assess late frost risk. Likewise, the number of days below +5 °C from March to May was regarded as a critical variable influencing flowering and fruit set.

Slightly sloped terrains (3–6 %) facilitate orchard management, harvesting, and accessibility while supporting mechanized operations. Such terrains also promote natural drainage of precipitation and meltwater, preventing waterlogging and protecting root systems. Slopes exceeding 10–12 % limit both yield and sustainable production (Popa et al., 2023). Accordingly, in this study, slopes of 2–8 % were considered highly suitable, while 8–12 % were moderately suitable.

Grange and Hand (1987) reported that when relative humidity is between 55% and 90% at 20°C (approximately 1.0 –0.2 kPa vapor pressure deficit) has little effect on the physiology and development of garden plants, while lower humidity levels cause water stress in plants, slowing growth, and higher humidity levels can promote diseases, leading to growth and development disorders. Başayiğit and Şenol (2008) reported that the most significant threats limiting fruit cultivation in areas with high fruit cultivation potential in Isparta province, as determined using Geographic Information Systems, are high groundwater levels and excessive moisture accumulation in the soil.

Verma (2014) emphasized that regions receiving less than 500 mm of annual precipitation are unsuitable for walnut cultivation. Since Kırşehir receives less than 500 mm annually, establishing and managing an efficient irrigation infrastructure is critical for sustainable walnut production.

Soleimani et al. (2018) utilized climatic parameters (temperature, relative humidity, precipitation, and wind speed), topography, and land data from 12 synoptic stations and neighboring provinces over an 11-year period (2004–2014) in Tehran to identify suitable sites for walnut cultivation. Temperature, relative humidity, and aspect were identified as the three most influential factors affecting walnut growth. Extreme temperatures above 38 °C can cause sunburn on walnut shells and shriveling of the fruit (Ahmad et al., 2018). This can negatively affect walnut shell and kernel development, leading to both yield reduction and decreased fruit quality. Therefore, temperatures exceeding 30°C in July and August have been considered an important climatic parameter. Since walnut flowers do not produce nectar, pollination does not occur via insects. Therefore, pollination is achieved by wind, and walnut trees produce a large amount of pollen to ensure effective fertilization (Keles, 2021). Consequently, wind speed and direction have a direct impact on pollination success. In Kırşehir and its districts, it was determined that wind speed does not pose a significant problem in areas where orchards are located; accordingly, wind influence was assigned a lower weight in the evaluation.

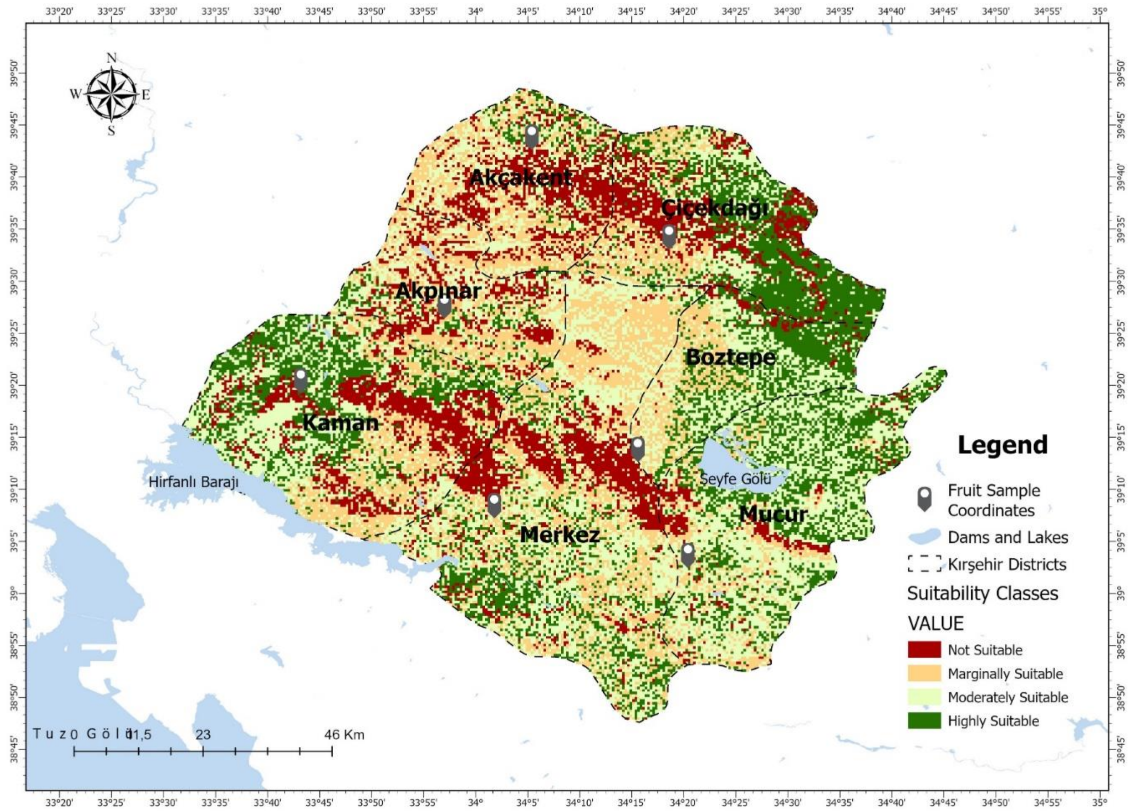

Figure 1. Climatic suitability map and fruit sampling locations for walnut (*Juglans regia* L.) cultivation in Kırşehir Province.

Fotirić Akšić et al. (2024) demonstrated that the AK (Alsószentiváni 117 × 'Pedro') walnut cultivar exhibits pollen tube growth and post-fertilization processes mediated by apomixis, which are better adapted to lower temperatures. These findings suggest that shifting walnut cultivation toward northern or higher-altitude regions with more continental climates may be advantageous.

Based on these parameters, the resulting suitability map (Figure 1) indicated that the most suitable areas for walnut cultivation are concentrated in the northwestern parts of Kaman, around the Hirfanlı Dam, and in the northeastern parts of Çiçekdağı and Boztepe districts. These areas offer favorable topographic and microclimatic conditions, including optimal slope, temperature range, and humidity balance. Moderately suitable and marginally suitable areas were mainly identified in Akçakent, Akpınar, and Mucur districts, where walnut productivity is limited due to less favorable climatic and topographic conditions. For instance, Gao et al. (2018) reported that the western and northern regions of China are suitable for walnut cultivation in terms of topography and climate. Similarly, Vahdati et al. (2019) indicated that the northern, northwestern and western parts of Iran are the most favorable for walnut cultivation, which aligns well with the current study's results for Kırşehir.

Pomological evaluation of walnut fruits revealed that the highest nut and kernel weights were obtained from Kaman and Çiçekdağı districts ($P<0.05$), while no significant differences were observed in kernel ratio ($P>0.05$). Nut thickness was highest in samples from Kaman district ($P<0.05$), and nut length was greatest in Kaman, Merkez, Boztepe, and Akpınar districts ($P<0.05$). Nut width was largest in Kaman, Çiçekdağı, Boztepe, and Akpınar ($P<0.05$), and shell thickness was highest in Kaman, Çiçekdağı, Akpınar, and Boztepe ($P<0.05$). Based on these pomological evaluations, Kaman, Boztepe, and Çiçekdağı were identified as the most suitable districts for walnut cultivation (Table 2).

Table 2. Mean values and statistical analysis of selected pomological traits of walnut fruits from Kırşehir Province and its districts (n=30)

District	n	Nut Weight (g)	Kernel Weight (g)	Kernel Ratio (%)	Nut Thickness (mm)	Nut Length (mm)	Nut Width (mm)	Shell Thickness (mm)
Kaman	30	16.69±0.9^{a}	8.17± 0.6^{a}	48.92±2.1	43.60±0.9^{a}	35.30±0.3^{a}	34.06±0.4^{a}	2.21±0.08^{a}
Merkez	30	10.44±0.5^{b}	4.53±0.2^{b}	44.47±2.5	36.40±0.7^{b}	36.47±0.7^{a}	29.80±0.7^{b}	1.47±0.07^{b}
Akçakent	30	11.98±1.1^{b}	5.28± 0.5^{b}	44.22±2.1	40.07±0.9^{b}	33.06±0.8^{b}	30.46±0.8^{b}	1.84±0.08^{c}
Mucur	30	11.89±0.6^{b}	5.74±0.4^{b}	48.20±3.1	37.52±1.1^{b}	32.81±0.6^{b}	30.96±0.6^{b}	1.71±0.09^{c}
Çiçekdağı	30	14.95±0.7^{a}	7.36±0.4^{a}	49.67±2.4	41.01±0.8^{b}	34.46±0.7^{b}	33.32±0.8^{a}	2.15±0.10^{a}
Akpınar	30	13.62±0.4^{b}	6.86±0.4^{ab}	52.16±2.7	39.14±0.6^{b}	37.45±1.3^{a}	34.35±0.7^{a}	1.93±0.07^{a}
Boztepe	30	13.6±0.9^{b}	6.21±0.6^{ab}	45.28±2.9	41.38±1.3^{b}	35.58±1.7^{a}	33.87±1.7^{a}	2.13±0.09^{a}

a, b: Different letters in the same column indicate significantly different treatment means ($P<0.05$).

Muradoğlu and Balta (2010) reported that walnut nut from the Ahlat region had weights ranging from 9.91 to 15.22 g, kernel weights of 5.00 to 6.24 g, and kernel ratios of 40.9–52.3 %. Kırca et al. (2014) conducted a study in Trabzon, where ten walnut genotypes obtained from seed-propagated populations exhibited nut weights ranging from 10.2 to 12.4 g, kernel weights between 5.2 and 6.7 g, and kernel ratios varying from 44.5% to 63.0%. In some of the selection types, nut weight and kernel weight were consistent with values reported in the literature, while in others the observed values were relatively low. The researchers reported that this may have resulted from ecological differences in the study areas and the genetic characteristics of the genotypes. The performance of a walnut orchard depends on both cultivar genetics and environmental conditions, highlighting the importance of adaptation studies across diverse ecological settings (Şen et al., 2018).

In Kırşehir, the prevailing continental climate and frequent late spring frosts make aspect and minimum temperature and number of days below 5 °C the most critical climatic parameters. GIS-based analysis identified the most suitable areas for walnut cultivation as the northern and northwestern parts of Kaman, the surroundings of Hirfanlı Dam, and the northeastern parts of Çiçekdağı and Boztepe districts.To ensure sustainable walnut production, soil quality in existing orchards should be regularly monitored, and new plantations should be established only after comprehensive site and feasibility evaluations. Considering frost risk and projected climate change effects will be crucial for maintaining productivity and long-term sustainability.

5. Conclusion

The climatic and topographic characteristics of Kırşehir province and its districts were evaluated, and fruit samples were collected from representative orchards identified under the guidance of the Kırşehir District Directorates of Agriculture. The analysis revealed that the most suitable areas for walnut cultivation are concentrated in the northwestern part of Kaman, around the Hirfanlı Dam, and in the northeastern parts of Çiçekdağı and Boztepe districts. In these regions, topography is favorable, extreme temperature events are limited, and relative humidity levels during spring and summer remain within optimal ranges. Areas of marginal suitability are dominant in Akpınar and Akçakent, whereas moderately suitable zones are more widespread in Mucur district.

Pomological evaluation indicated that although many orchards are located within moderately or marginally suitable zones, Kaman stands out with the highest nut and kernel weights. Consequently, Kaman emerges as the most favorable district for walnut cultivation based on both climatic-topographic suitability and pomological characteristics. The GIS-based AHP findings were consistent with field observations, reinforcing the reliability of the spatial analysis. However, the occurrence of genotypes with desirable traits such as high nut weight and kernel ratio in areas classified as moderately or marginally suitable suggests that walnut performance is influenced not only by climatic and topographic conditions but also by genetic characteristics, irrigation availability, orchard management practices, and microclimatic effects. Therefore, while the land suitability maps provide an overview of the general potential for walnut cultivation, local scale genetic variation and environmental interactions can substantially affect pomological outcomes.

According to the Regulation on Agricultural Production Planning issued on 14 September 2023, Boztepe and Mucur districts have been designated as areas with limited groundwater availability. In line with this regulation, insufficient groundwater potential and the need to conserve existing water resources restrict water-intensive agricultural activities in these districts. Consequently, the cultivation of long-lived fruit species with relatively highwater requirements, such as walnut, is considered unsuitable in these areas. Although the spatial analyses indicate partial suitability for walnut cultivation in certain parts of Boztepe and Mucur, the water-limited basin conditions prevent this potential from being fully realized in agricultural production. Overall, these findings emphasize that sustainable management of water resources, alongside climatic and topographic factors, should be a fundamental component of regional agricultural planning and the future expansion of walnut orchards in Kırşehir province.

Author Contributions

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

	E.Ş.	Y.E.
C	60	40
D	60	40
S	60	40
DCP	70	30
DAI	60	40
L	70	30
W	70	30
CR	60	40
SR	70	30
PM	60	40

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because there was no study on animals or humans.

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