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Comparative effects of conventional and air-frying cooking methods on phenolic compounds and antioxidant capacity in brassica vegetables

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Research Article

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Abstract

Brassica vegetables are rich sources of phenolic compounds and antioxidants; however, thermal processing may significantly alter their bioactive composition. This study evaluated the effects of boiling, steaming, oven cooking, and air frying on total phenolic content (TPC), total flavonoid content (TFC), antioxidant activity (FRAP, CUPRAC, and DPPH), pH, and total acidity in broccoli, cauliflower, and Brussels sprouts. Significant differences were observed among both vegetable types and cooking methods ($p < 0.05$). Brussels sprouts exhibited the highest TPC, TFC, FRAP, and CUPRAC values, whereas cauliflower showed the lowest antioxidant properties. Among the cooking methods, boiling resulted in the greatest reductions in phenolic compounds, flavonoids, and antioxidant activity, indicating substantial losses of water-soluble bioactive compounds during thermal processing. In contrast, air frying and steaming better preserved antioxidant properties and phenolic compounds. Air-fried samples exhibited particularly high flavonoid content and FRAP values, while steaming showed favorable antioxidant retention without direct water contact. Cooking treatments generally decreased pH values and increased total acidity compared with raw samples. Overall, the findings suggest that cooking method plays a critical role in preserving the nutritional and functional quality of Brassica vegetables. Air frying and steaming may represent more suitable domestic cooking methods for maintaining antioxidant capacity and bioactive compounds compared with conventional boiling.

Introduction

Reactive oxygen species (ROS) and free radicals are continuously generated during normal metabolic processes in the human body. Excessive accumulation of these reactive molecules may induce oxidative stress by causing oxidative damage to cellular biomolecules such as lipids, proteins, and DNA. Oxidative stress has been associated with the development of several chronic disorders, including cardiovascular diseases, diabetes mellitus, neurodegenerative diseases, and certain types of cancer (Janciauskiene, 2020; Neha et al., 2019). To counteract the harmful effects of ROS and free radicals, the human body utilizes antioxidant compounds such as vitamins, flavonoids, phenolic acids, and other phytochemicals. Therefore, regular consumption of fruits and vegetables rich in antioxidant compounds may contribute to reducing oxidative stress and promoting human health (Jideani et al., 2021; Zehiroglu & Ozturk Sarikaya, 2019).

Brassica vegetables, including broccoli, cauliflower, and Brussels sprouts, are important dietary sources of bioactive compounds due to their rich phytochemical composition. These vegetables contain considerable amounts of glucosinolates, phenolic compounds, flavonoids, vitamins, and other functional metabolites (Bhandari & Kwak, 2015). Upon tissue disruption, glucosinolates are hydrolyzed by the enzyme myrosinase to form isothiocyanates, which have been reported to support antioxidant defense mechanisms (Becker & Juvik, 2016). Sulfur-containing isothiocyanates, in particular, may reduce oxidative stress and exhibit protective effects against certain cancers. In addition, phenolic compounds and flavonoids contribute to antioxidant activity through their free radical scavenging capacity. Owing to

these properties, Brassica vegetables are widely recognized as valuable functional foods with potential health-promoting effects (Andrés et al., 2025; Iwar et al., 2024).

Thermal processing can significantly influence the phytochemical composition and antioxidant capacity of vegetables. Heat treatment may enhance the release of bound phenolic compounds and flavonoids by disrupting plant cell walls, thereby increasing the extractability of certain bioactive compounds. Conversely, prolonged exposure to high temperatures may result in the degradation or leaching of heat-sensitive and water-soluble compounds. In Brassica vegetables, thermal processing may also inactivate myrosinase, affecting the conversion of glucosinolates into biologically active isothiocyanates (Jiang et al., 2023; Murador et al., 2018; Pérez-Burillo et al., 2019).

Several studies have investigated the effects of cooking methods on the phytochemical composition and antioxidant properties of Brassica vegetables. However, comparative studies evaluating broccoli, cauliflower, and Brussels sprouts simultaneously under the same experimental conditions remain limited, particularly with respect to modern cooking techniques such as air frying (Wachtel-Galor et al., 2008; Reis et al., 2015; Miškec et al., 2025). In recent years, air frying has gained increasing popularity as a domestic cooking method due to its reduced oil usage and rapid cooking conditions. Nevertheless, available data regarding the effects of air frying on the antioxidant profile and phenolic composition of Brassica vegetables are still insufficient.

In addition to conventional cooking methods such as boiling, steaming, and oven cooking, the present study also evaluated air frying, a relatively underexplored thermal processing technique in Brassica vegetables. Furthermore, broccoli, cauliflower, and Brussels sprouts were investigated simultaneously under the same experimental conditions, allowing direct comparison of species-specific responses to thermal processing. Multiple physicochemical and antioxidant parameters, including total phenolic content, total flavonoid content, FRAP, CUPRAC, DPPH, pH, and total acidity, were comprehensively evaluated to assess the effects of thermal processing on Brassica vegetables.

Therefore, the aim of this study was to compare the effects of different cooking methods, including boiling, steaming, oven cooking, and air frying, on the antioxidant activity, phenolic composition, pH, and total acidity of broccoli, cauliflower, and Brussels sprouts.

Materıals and Methods

Materials

This experimental study was conducted between October 2025 and May 2026 in the Chemistry Laboratory of Istanbul Esenyurt University. Broccoli, cauliflower, and Brussels sprouts samples were purchased from a local public market located in the Esenyurt district of Istanbul, Türkiye. Each vegetable type was obtained in an amount of 1 kg. To preserve freshness and nutritional quality, the vegetables were cleaned immediately after purchase, washed thoroughly with tap water, and dried using paper

towels. No storage treatment was applied prior to processing. Before cooking, each vegetable sample was cut into uniform pieces and weighed into 100 g portions using a precision balance.

Cooking Procedures

Steaming

Fifty milliliters of water was added to a stainless-steel pot and heated until boiling. A metal strainer was placed over the pot, and 100 g of vegetable samples were transferred into the strainer. The pot was covered with a lid, and the samples were steamed over low heat for 15 min.

Boiling

Five hundred milliliters of water was added to a stainless-steel pot and brought to boiling. Subsequently, 100 g of vegetable samples were immersed in the boiling water. The pot was covered with a lid, and the samples were boiled over low heat for 15 min.

Oven Cooking

Each vegetable sample (100 g) was placed separately on baking trays and cooked in a preheated conventional oven at 180°C for 30 min.

Air Frying

Each vegetable sample (100 g) was placed separately in the basket of an air fryer and cooked at 180°C for 10 min.

Determination of Cooking Conditions

Cooking temperatures and processing times were selected to represent commonly applied domestic cooking conditions for Brassica vegetables and were established based on previously published studies. The 15 min steaming and boiling treatments were considered sufficient to achieve adequate softening while enabling the evaluation of changes in phenolic compounds and antioxidant capacity. Similar processing conditions have been previously reported for broccoli and cauliflower (Lopez-Hernández et al., 2022; Hwang, 2019). The temperature of 180°C selected for oven and air-frying treatments represents a commonly used dry-heat cooking condition for Brassica vegetables. Previous studies have suggested that short-term high-temperature air frying may contribute to the preservation of phenolic compounds and antioxidant activity (Nandasiri et al., 2023; Miškec et al., 2025). Therefore, the cooking conditions applied in this study were selected to both reflect domestic consumption practices and allow comparison of the effects of different cooking methods on bioactive compounds.

Methods

pH Analysis

The pH values of raw and cooked vegetable samples were determined according to AOAC Method No. 981.12 (AOAC, 1990).

Determination of Total Acidity

Total acidity values, expressed as acetic acid equivalents, were determined according to AOAC Method No. 942.15 (AOAC, 1990).

Extraction Procedure

Prior to analysis, vegetable samples were dried in an oven at 40°C until constant weight was achieved. The dried samples were ground to obtain a homogeneous powder, and 1 g of each sample was weighed. Subsequently, 30 mL of distilled water was added, and extraction was performed in an ultrasonic water bath for 5 min at room temperature. The extracts were then centrifuged at 5000 rpm for 10 min using a centrifuge, and the obtained supernatants were filtered through a 0.45 µm membrane filter. The resulting extracts were used for total phenolic content, total flavonoid content, and antioxidant activity analyses (Dent et al., 2013).

Determination of Total Phenolic Content

Total phenolic content (TPC) was determined using the Folin–Ciocalteu method described by Singleton and Rossi (1965). Absorbance values were measured at 765 nm using a UV–Vis spectrophotometer, and the results were expressed as mg gallic acid equivalent per gram dry weight (mg GAE/g DW).

Determination of Total Flavonoid Content

Total flavonoid content (TFC) was determined according to the method described by Zhishen et al. (1999). Absorbance values were measured at 510 nm using a UV–Vis spectrophotometer, and the results were expressed as mg quercetin equivalent per gram dry weight (mg QE/g DW).

Ferric Reducing Antioxidant Power (FRAP) Assay

Ferric reducing antioxidant power (FRAP) analysis was performed according to the method of Benzie and Strain (1996). Absorbance values were measured at 593 nm using a UV–Vis spectrophotometer, and the results were expressed as mg Trolox equivalent per gram dry weight (mg TE/g DW).

Cupric Reducing Antioxidant Capacity (CUPRAC) Assay

Cupric reducing antioxidant capacity (CUPRAC) analysis was conducted according to the method developed by Apak et al. (2004). Absorbance values were measured at 450 nm using a UV–Vis spectrophotometer, and the results were expressed as mg TE/g DW.

DPPH Radical Scavenging Activity Assay

DPPH radical scavenging activity was determined according to the method of Brand-Williams et al. (1995). Absorbance values were measured at 517 nm using a UV–Vis spectrophotometer, and the results were expressed as mg TE/g DW.

Statistical Analysis

All measurements were conducted in triplicate, and results were expressed as mean ± standard deviation. Statistical analyses were performed using IBM SPSS Statistics 25 software (IBM Corp., Armonk, NY, USA). Prior to analysis, data were evaluated for normality and homogeneity of variance assumptions. Two-way analysis of variance (ANOVA) was applied to determine the effects of vegetable type and cooking method, as well as their interaction effects, on the investigated parameters. Duncan's multiple range test was used for post hoc comparisons between group means. Statistical significance was accepted at $p < 0.05$.

Results and Discussion

Statistically significant differences were observed among the vegetable samples in terms of pH and total acidity values ($p < 0.01$). The highest pH value was determined in Brussels sprouts (5.82), followed by broccoli (5.79) and cauliflower (5.74). In terms of total acidity, the highest value was detected in broccoli samples (3.71 g/100 g), followed by Brussels sprouts (3.45 g/100 g), whereas the lowest total acidity value was observed in cauliflower samples (2.14 g/100 g). Shokri et al. (2022) reported pH and titratable acidity values of 6.84 and 4.30 g/L, respectively, in broccoli purée samples. Similarly, Iga-Buitrón et al. (2023) determined the pH value of broccoli as 5.8 in a fermentation study. Bilgin and Aslantaş (2022) reported pH and titratable acidity values ranging between 5.80–6.05 and 0.16–0.17, respectively, in Brussels sprouts. In another study conducted on Brassica species, Qinghang et al. (2023) reported pH and titratable acidity values of 5.46 and 0.54 g/100 g, respectively, for cauliflower.

The effects of cooking methods on pH and total acidity were also found to be statistically significant ($p < 0.05$; $p < 0.01$). The highest pH value was observed in the raw control group (5.97), whereas the lowest value was detected in air-fried samples (5.58). Steaming (5.72) and oven cooking (5.77) also resulted in reductions in pH values. Regarding total acidity, the highest values were obtained in oven-cooked (3.27 g/100 g), air-fried (3.25 g/100 g), and steamed samples (3.22 g/100 g), while the lowest total acidity value was determined in boiled samples (2.77 g/100 g). Compared with the raw control samples, the decrease in pH and increase in total acidity following thermal processing may be attributed to the release of organic acids and the disruption of cellular structures during cooking.

Table 1
Effects of different vegetable types and cooking methods on pH and total acidity values

Samples (S) / Parameters	N	pH	Total Acidity (g/100 g)
Cauliflower	15	5.74 ± 0.12c	2.14 ± 0.63c
Broccoli	15	5.79 ± 0.25b	3.71 ± 0.69a
Brussels sprouts	15	5.82 ± 0.11a	3.45 ± 0.55b
Significance		**	**
Cooking Methods (CM)			
Raw (Control)	9	5.97 ± 0.04a	2.98 ± 0.32ab
Steaming	9	5.72 ± 0.02d	3.22 ± 1.19a
Boiling	9	5.88 ± 0.18b	2.77 ± 0.60b
Oven cooking	9	5.77 ± 0.02c	3.27 ± 1.31a
Air frying	9	5.58 ± 0.15e	3.25 ± 0.96a
Significance		**	*
S × CM		**	**

Values are expressed as mean ± standard deviation. Different superscript letters within the same column indicate significant differences between groups ($p < 0.05$). *$p < 0.05$; **$p < 0.01$.

Statistically significant differences were observed among the vegetable samples in terms of total phenolic content (TPC) and total flavonoid content (TFC) ($p < 0.01$). The highest TPC value was determined in Brussels sprouts (9.21 ± 1.61 mg GAE/g DW), followed by broccoli (7.05 ± 2.80 mg GAE/g DW) and cauliflower (6.24 ± 1.68 mg GAE/g DW). Similarly, the highest total flavonoid content was also observed in Brussels sprouts (6.15 ± 4.61 mg QE/g DW), whereas broccoli (3.04 ± 2.08 mg QE/g DW) and cauliflower (2.37 ± 2.29 mg QE/g DW) exhibited lower values.

The effects of cooking methods on TPC and TFC were found to be statistically significant ($p < 0.01$). The highest TPC value was observed in the raw control group (9.87 ± 1.29 mg GAE/g DW), while the lowest value was detected in boiled samples (5.93 ± 1.40 mg GAE/g DW). Air frying (8.55 ± 2.37 mg GAE/g DW) was found to be more effective in preserving phenolic compounds compared with the other cooking methods. In terms of total flavonoid content, the highest value was obtained in air-fried samples (8.46 ± 4.37 mg QE/g DW), followed by the raw control group (4.76 ± 0.81 mg QE/g DW). The lowest flavonoid content was determined in boiled samples (0.70 ± 0.46 mg QE/g DW). Overall, boiling resulted in considerable losses in most parameters, whereas air frying and steaming better preserved or enhanced certain antioxidant-related properties.

In the present study, boiling generally produced the lowest values for total phenolic content, total flavonoid content, and antioxidant activity. This reduction may be attributed to the leaching of phenolic compounds, flavonoids, and other water-soluble antioxidant compounds into the cooking water during thermal processing. Thermal degradation of heat-sensitive antioxidant compounds may have additionally contributed to these reductions. Previous studies have similarly reported the adverse effects of boiling on phenolic compounds and antioxidant capacity. Lopez-Hernández et al. (2022) reported that conventional boiling caused substantial losses in the total polyphenol content of broccoli. Likewise, Hwang (2019) demonstrated that boiled cauliflower exhibited lower total polyphenol content, total flavonoid content, and antioxidant activity compared with raw and steamed samples. The findings obtained in the present study are consistent with those reported in the literature.

Table 2
Effects of different vegetable types and cooking methods on total phenolic content and total flavonoid content

Samples (S) / Parameters	**N**	**TPC (mg GAE/g DW)**	**Total Flavonoid Content (mg QE/g DW)**
Cauliflower	15	6.24 ± 1.68c	2.37 ± 2.29c
Broccoli	15	7.05 ± 2.80b	3.04 ± 2.08b
Brussels sprouts	15	9.21 ± 1.61a	6.15 ± 4.61a
Significance		**	**
Cooking Methods (CM)			
Raw (Control)	9	9.87 ± 1.29a	4.76 ± 0.81b
Steaming	9	6.87 ± 2.68c	2.09 ± 1.29d
Boiling	9	5.93 ± 1.40e	0.70 ± 0.46e
Oven cooking	9	6.28 ± 1.78d	3.26 ± 2.78c
Air frying	9	8.55 ± 2.37b	8.46 ± 4.37a
Significance		**	**
S × CM		**	**

Values are expressed as mean ± standard deviation. Different superscript letters within the same column indicate significant differences between groups ($p < 0.05$). *$p < 0.05$; **$p < 0.01$. TPC: Total phenolic content; DW: Dry weight.

Significant differences in antioxidant activity were observed among both vegetable species and cooking methods ($p < 0.01$). Brussels sprouts generally exhibited the highest FRAP and CUPRAC values, whereas broccoli showed the strongest DPPH radical scavenging activity. These differences suggest that antioxidant capacity was strongly influenced by the inherent phytochemical composition of each Brassica species.

Cooking methods markedly affected antioxidant activity. Boiling generally resulted in the lowest antioxidant values across all assays, indicating substantial losses of water-soluble antioxidant compounds during thermal processing. In contrast, steaming and air frying better preserved antioxidant capacity, particularly in FRAP analysis. The higher antioxidant retention observed in these methods may be associated with reduced leaching losses and improved release of bound phenolic compounds due to controlled thermal disruption of plant tissues. Although raw samples exhibited the highest DPPH and CUPRAC values in certain analyses, dry-heat treatments such as air frying maintained antioxidant properties more effectively than boiling.

The preservation of antioxidant compounds during steaming may be attributed to the absence of direct contact between the vegetables and water, thereby reducing the leaching of phenolic compounds. In addition, short-term thermal processing may disrupt cellular structures and enhance the release of bound phenolic compounds. Lopez-Hernández et al. (2022) reported increases in DPPH, ABTS, and FRAP values following steaming treatment in broccoli samples. Similarly, Seçmeler et al. (2024) demonstrated that steaming yielded one of the highest total phenolic content values in cauliflower. The positive effects of steaming observed in the present study, particularly regarding ferric reducing antioxidant capacity, are therefore consistent with previous findings.

In air-fried samples, the lack of direct water contact and the application of short-term dry heat may reduce the loss of phenolic compounds into the cooking medium. Furthermore, elevated temperatures may contribute to the release of bound phenolics through disruption of plant cell walls. In addition, moisture reduction during air frying may increase the relative concentration of extractable antioxidant compounds in vegetable tissues. Controlled dry-heat exposure may also facilitate the release of bound phenolic compounds without causing the extensive leaching losses typically associated with boiling. Nandasiri et al. (2023) reported that air frying enhanced total phenolic content, total flavonoid content, and antioxidant activity in Brassica vegetables. Likewise, Miškec et al. (2025) demonstrated that air-fried broccoli retained high levels of glucosinolates, hydroxycinnamic acids, carotenoids, lycopene, and antioxidant capacity. The authors also reported that steaming and air frying were more effective in preserving total phenolic compounds and exhibited the highest antioxidant activity according to DPPH analysis. The findings of the present study support the hypothesis that air frying may contribute to the preservation of bioactive compounds in Brassica vegetables, particularly under short-duration and low-moisture cooking conditions.

The relatively lower antioxidant activity observed in oven-cooked samples may be associated with the degradation of certain heat-sensitive phenolic compounds during prolonged dry-heat exposure. However, previous studies have also suggested that Maillard reaction products formed during oven cooking may exhibit antioxidant properties. Seçmeler et al. (2024) reported that oven cooking increased total phenolic content in cauliflower, possibly due to the release of bound phenolic compounds. Therefore, the effects of oven cooking may vary depending on cooking temperature, processing time, and vegetable type.

The high antioxidant activity observed in raw control samples, particularly in DPPH and certain phenolic analyses, suggests that some antioxidant compounds are sensitive to thermal processing. Hwang (2019) reported higher total polyphenol content and antioxidant activity in raw cauliflower compared with boiled samples. Similarly, Hwang (2017) demonstrated that raw Brussels sprouts exhibited the highest antioxidant activity. The present findings further indicate that thermal processing may reduce the concentration of heat-sensitive antioxidant compounds.

Differences observed among vegetable types may also be related to their inherent phenolic and flavonoid profiles rather than cooking methods alone. Previous studies have demonstrated substantial variation in phenolic composition among Brassicaceae species. A study conducted on Brassicaceae vegetables grown in Çanakkale reported high total phenolic content and ABTS antioxidant activity in Brussels sprouts and red cabbage (Önder et al., 2020). These findings suggest that different Brassica species may respond differently to thermal processing.

The CUPRAC assay used in the present study has been less frequently applied in the literature compared with DPPH and FRAP methods. Mahomoodally et al. (2018) reported that the CUPRAC assay operates under conditions closer to physiological pH and may therefore evaluate the reducing capacity of certain antioxidant compounds differently. Consequently, complete agreement between FRAP and CUPRAC results may not always be expected. Variations among antioxidant assays are commonly reported in the literature, as each method is based on different reaction mechanisms.

Table 3
Effects of different vegetable types and cooking methods on antioxidant activity values

Samples (S) / Parameters	**N**	**FRAP (mg TE/g DW)**	**CUPRAC (mg TE/g DW)**	**DPPH (mg TE/g DW)**
Cauliflower	15	4.87 ± 2.54c	3.81 ± 1.59c	2.48 ± 1.44c
Broccoli	15	9.38 ± 3.79b	5.85 ± 2.62b	3.50 ± 2.81a
Brussels sprouts	15	11.71 ± 5.29a	7.88 ± 1.83a	3.32 ± 2.99b
Significance		**	**	**
Cooking Methods (CM)				
Raw (Control)	9	4.69 ± 1.69d	7.69 ± 2.88a	6.44 ± 2.18a
Steaming	9	11.68 ± 6.87a	6.14 ± 3.43c	3.25 ± 2.25c
Boiling	9	4.72 ± 2.18d	4.45 ± 2.88e	0.83 ± 0.66e
Oven cooking	9	10.70 ± 2.79c	4.62 ± 0.76d	1.54 ± 1.47d
Air frying	9	11.46 ± 3.07b	6.33 ± 0.94b	3.45 ± 0.78b
Significance		**	**	**
S × CM		**	**	**

Values are expressed as mean ± standard deviation. Different superscript letters within the same column indicate significant differences between groups ($p < 0.05$). *$p < 0.05$; **$p < 0.01$. FRAP: Ferric reducing antioxidant power; CUPRAC: Cupric reducing antioxidant capacity; DPPH: 2,2-diphenyl-1-picrylhydrazyl; DW: Dry weight.

Conclusions

The present study demonstrated that different cooking methods significantly influenced pH, total acidity, phenolic compounds, and antioxidant capacity in Brassica vegetables. Overall, Brussels sprouts exhibited higher phenolic content and antioxidant activity compared with broccoli and cauliflower. Among the cooking methods evaluated, boiling caused substantial reductions in total phenolic content (5.93 mg GAE/g DW), total flavonoid content (0.70 mg QE/g DW), and antioxidant activity values (FRAP: 4.72 mg TE/g DW; CUPRAC: 4.45 mg TE/g DW; DPPH: 0.83 mg TE/g DW). In contrast, air frying produced some of the highest values, particularly for total flavonoid content (8.46 mg QE/g DW) and FRAP activity (11.46 mg TE/g DW). Steaming and oven cooking exhibited moderate protective effects on antioxidant-related properties. Cooking treatments generally reduced pH values compared with the raw control group (5.97), with values of 5.58, 5.72, 5.77, and 5.88 observed for air frying, steaming, oven cooking, and boiling, respectively. Correspondingly, total acidity increased following thermal processing, with the highest acidity value detected in broccoli samples (3.71 g/100 g). Overall, the findings indicate that cooking method plays a critical role in the preservation of bioactive compounds in Brassica vegetables. Boiling resulted in the greatest losses of phenolic compounds and antioxidant capacity, whereas air frying and steaming emerged as more protective cooking methods. In particular, the ability of air frying to preserve flavonoids and antioxidant capacity suggests that this method may represent a promising alternative for maintaining the nutritional quality of Brassica vegetables. However, a limitation of the present study is that glucosinolate degradation products and bioaccessibility of antioxidant compounds were not evaluated. Future studies should investigate the effects of thermal processing on glucosinolate-derived compounds and the bioavailability of bioactive constituents in Brassica vegetables. These findings may contribute to the development of healthier domestic cooking practices and support the selection of cooking methods that better preserve the nutritional and functional properties of Brassica vegetables.

Declarations

Ethical Approval

Not Applicable.

Informed Consent

Not Applicable.

Conflict of interest

The authors declare no conflict of interest.

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The study received no external funding.

Author Contribution

Concept: B.E., H.İ.B., Design: B.E., H.İ.B., Data collection or Processing: H.İ.B., Analysis or Interpretation: H.İ.B., Literature Search: B.E., H.İ.B., Writing: B.E., H.İ.B., Editing: H.İ.B., B.E.

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