



# Comparative Evaluation of Biological Activities and Metal-binding Properties of Three *Teucrium* Species from Türkiye

Hülya Şen Arslan<sup>1,4</sup> · Bahar Yılmaz Altınok<sup>2</sup> · Ömer Çeçen<sup>3</sup>

Received: 16 January 2026 / Accepted: 24 May 2026 / Published online: 2 June 2026

© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2026

## Abstract

This study aimed to comparatively evaluate the phytochemical composition, biological activities, and metal-binding properties of phenolic-rich extracts obtained from *Teucrium polium* (TPE), *Teucrium orientale* (TOE), and *Teucrium turcicum* (TTE). Total phenolic content, antioxidant activity,  $\alpha$ -glucosidase inhibitory effect, antibacterial activity, and in vitro cytotoxicity were determined using spectrophotometric and bioanalytical techniques. In addition, FTIR, UV–Vis spectroscopy, fluorescence quenching, and Job's plot analyses were performed to investigate metal–extract interactions and complex formation behavior. Among the investigated extracts, TPE exhibited the highest total phenolic content (39.43 mg GAE/L) together with the strongest antioxidant activity (DPPH EC<sub>50</sub> = 2.70 mg/mL). TPE also demonstrated notable  $\alpha$ -glucosidase inhibitory activity with an IC<sub>50</sub> value of 6.88 mg/mL. In antibacterial analyses, TOE showed the strongest inhibitory effect, particularly against *Streptococcus mutans* and *Escherichia coli*. Spectroscopic analyses revealed selective interactions of TTE and TPE with Hg<sup>2+</sup> ions and TOE with Cu<sup>2+</sup> ions. Fluorescence quenching and Job's plot analyses confirmed selective 1:1 complex formation between the extracts and target metal ions. Cytotoxicity assays demonstrated concentration-dependent effects against HT-29 and CaCo-2 colorectal cancer cell lines. The IC<sub>50</sub> values for HT-29 cells were determined as 178.4  $\mu$ g/mL for TPE, 192.6  $\mu$ g/mL for TTE, and 261.3  $\mu$ g/mL for TOE, whereas the corresponding IC<sub>50</sub> values for CaCo-2 cells were 134.8  $\mu$ g/mL, 148.5  $\mu$ g/mL, and 207.4  $\mu$ g/mL, respectively. In contrast, L929 fibroblast cells exhibited comparatively higher viability under the tested conditions. FTIR analyses suggested that hydroxyl and aromatic oxygen-containing functional groups play a major role in metal coordination and complex stabilization. Overall, the findings indicate that phenolic-rich *Teucrium* extracts possess multifunctional biological activities together with selective metal-binding properties, highlighting their potential for future studies involving natural bioactive compounds and sensing-related applications.

## Highlights

- Bioactive potential, antibacterial efficacy, anticancer activity, and metal-binding properties of three *Teucrium* species (*T. polium*, *T. orientale*, and *T. turcicum*).
- *T. polium* exhibit the highest phenolic content, remarkable antioxidant capacity, strong  $\alpha$ -glucosidase inhibition, and superior antibacterial activity.
- These extracts play a central role in metal coordination, conferring high selectivity toward Hg<sup>2+</sup> (*T. polium*, *T. turcicum*) and Cu<sup>2+</sup> (*T. orientale*).

**Keywords** Antioxidant · Antidiabetic · Antibacterial · Cytotoxicity · Selective metal binding properties

✉ Hülya Şen Arslan  
hsenarslan@kmu.edu.tr

<sup>1</sup> Department of Food Engineering, Karamanoğlu Mehmetbey University, Faculty of Engineering, Karaman 70200, Türkiye

<sup>2</sup> Department of Bioengineering, Karamanoğlu Mehmetbey University, Faculty of Engineering, 70200 Karaman, Türkiye

<sup>3</sup> Department of Biology, Kamil Özdağ Faculty of Science, Karamanoğlu Mehmetbey University, Karaman 70200, Türkiye

<sup>4</sup> Department of Food Engineering, Necmettin Erbakan University, Faculty of Engineering, Konya, Türkiye

## Introduction

The *Lamiaceae* family comprises approximately 236 genera and 7,000 species worldwide and has long been recognized for its medicinal importance [1]. In Türkiye, *Lamiaceae* is represented by 48 genera and 603 species, including numerous endemic taxa. The genus *Teucrium* includes 35 taxa distributed in Türkiye, 16 of which are endemic. Among these, *Teucrium turcicum* has been identified as an endemic species restricted to Türkiye [2, 3]. Despite the growing scientific interest in *Teucrium* species, comprehensive studies focusing on the phytochemical composition, biological activities, and metal-binding properties of endemic *T. turcicum* and *Teucrium orientale* remain limited.

Natural products and plant-derived compounds have attracted considerable attention due to their antioxidant, antimicrobial, cytotoxic, and enzyme inhibitory properties [4–11]. In particular, phenolic compounds and flavonoids are recognized as major bioactive metabolites responsible for many of these biological effects. Recent studies demonstrated that phenolic-rich extracts from *Teucrium montanum* and *Teucrium capitatum* exhibit strong antioxidant and antibacterial activities, highlighting the close relationship between phenolic profile and biological activity [12, 13]. Moreover, phenolic-rich plant extracts are considered promising sources for the development of alternative bioactive agents, although further studies are still required to clarify their broader therapeutic potential [14, 15].

Phenolic compounds are also capable of coordinating with metal ions through hydroxyl, carboxyl, and aromatic functional groups. These metal–phenolic interactions may induce detectable spectroscopic changes such as fluorescence quenching and absorption shifts, making natural phenolics promising candidates for environmentally friendly sensing systems. Recent studies have emphasized the potential of metal–phenolic interactions in analytical sensing applications, particularly for the selective detection of heavy metal ions [16]. In addition, fluorescence-based chemosensors have gained increasing attention due to their sensitivity and practical applicability in monitoring environmental and metal-related stress factors [17]. Beyond sensing applications, the metal-binding capacity of phenolic compounds is also important for food safety and functional food development, particularly in controlling heavy metal contamination in food systems while simultaneously supporting antioxidant stability [18, 19].

Despite the growing interest in the genus *Teucrium*, studies addressing the multifunctional potential of endemic *Teucrium turcicum* and *Teucrium orientale* remain extremely limited. The present study provides a novel and comprehensive investigation by integrating biological activity screening with spectroscopic heavy metal-binding analyses, an

approach that has not previously been reported for these species. To the best of our knowledge, this is the first study to comparatively evaluate the antioxidant, antimicrobial, and anticancer properties of these endemic taxa together with their metal interaction behavior within the context of potential biosensor-related applications. The scientific significance of this integrated strategy lies in establishing a direct relationship between the bioactive phytochemical profile and the metal-chelating capacity of the extracts, thereby extending the relevance of these species beyond conventional pharmacological investigations toward analytical and environmental technologies. Accordingly, the findings of the present study not only fill an important gap in the literature concerning endemic *Teucrium* species, but also introduce a multidisciplinary perspective that may contribute to the future development of plant-based therapeutic and biosensor systems.

## Materials and Methods

### Plant Material and Chemicals

All chemicals employed in this study were of analytical grade and obtained from Sigma-Aldrich, Türkiye. *Teucrium turcicum* Çeçen & Özcan and *Teucrium polium* L. were collected on 12 May 2025 from the vicinity Çukurabanoz village of Anamur district, Mersin Province, Türkiye, at an altitude of 652–843 m. *Teucrium orientale* L. was collected on 28 June 2025 from the vicinity of Ermenek district, Karaman Province, Türkiye, at an altitude of 1452–1525 m. Plant specimens were collected and species identified by plant taxonomist Dr. Ömer ÇEÇEN. The voucher specimens has been deposited in the Herbarium of Karamanoğlu Mehmetbey University (KMUB) with the registration numbers KMUB 8224 (*Teucrium turcicum*), KMUB 8225 (*Teucrium polium*), KMUB 8262 (*Teucrium orientale*). Collected plant materials were air-dried in the shade and subsequently, the leaves were carefully separated from the stems. Leaves were selected for the study due to their rich phenolic and flavonoid content, homogeneous phytochemical composition, and suitability for sustainable sampling. The leaf samples were then finely ground using a laboratory mill and stored at −18 °C until further extraction procedures.

### Preparation of Extracts

Methanolic extracts were prepared according to the method described by Şen Arslan and Çam (2022) [20]. Briefly, 20 g of powdered leaves with approximately 5% moisture content were extracted with 200 mL of 80% methanol in a shaking water bath at 50 °C and 120 rpm for 2 h. The

mixtures were then centrifuged at  $1860 \times g$  for 10 min, and the supernatants were filtered through Whatman No. 1 filter paper. The obtained crude extracts were directly used in subsequent analyses without evaporation or reconstitution steps and were stored in sterile bottles at  $-18\text{ }^{\circ}\text{C}$  until use. All biological and metal interaction assays were performed using the crude methanolic extracts under identical extraction conditions for both species. Additionally, the preparation of extract concentrations used in each assay was described in detail. Briefly, extracts were diluted 50–200 fold for TPC and DPPH assays, 50 fold for the ABTS assay, and 10–50 fold for the  $\alpha$ -glucosidase inhibition assay prior to analysis.

### Determination of Total Phenolic Content

The total phenolic content (TPC) of the extracts was measured following Cam and Icyer (2015) [21]. Results were expressed as mg gallic acid equivalents (GAE)/L.

### Antioxidant Activity Assays

Antioxidant capacity was evaluated using DPPH and ABTS radical scavenging assays. The ABTS assay was conducted according to Fan et al. (2015) [22], and DPPH activity was measured based on Fernandes et al. (2016) [23]. The effective concentration ( $\text{EC}_{50}$ ) values (mg/mL) were calculated for each extract.

### $\alpha$ -Glucosidase Inhibitory Activity

The inhibitory effect on  $\alpha$ -glucosidase was assessed using a colorimetric method [20, 24]. In brief, 1250  $\mu\text{L}$  of 67 mM  $\text{KH}_2\text{PO}_4$  buffer (pH 6.8), 50  $\mu\text{L}$  of diluted extract, and 50  $\mu\text{L}$   $\alpha$ -glucosidase solution (0.2 U/mL) were incubated at  $37\text{ }^{\circ}\text{C}$  for 5 min. The reaction was initiated with 125  $\mu\text{L}$  of 10 mM 4-nitrophenyl  $\alpha$ -D-glucopyranoside and stopped after 20 min by adding 2000  $\mu\text{L}$  of 0.1 M  $\text{Na}_2\text{CO}_3$ . Acarbose was used as a control. Absorbance was recorded at 400 nm, and  $\text{IC}_{50}$  values (mg/mL) were calculated.

### Antibacterial Activity

Minimum inhibitory concentrations (MIC) of the extracts were determined using the microdilution method. For the MIC analyses, extract concentrations ranging from 500 to 100,000 ppm were prepared using serial dilution to determine the minimum inhibitory and bactericidal concentrations. Cultures of *Staphylococcus aureus* ATCC 29,213, *Streptococcus mutans* ATCC 700,610, *Escherichia coli* ATCC 25,922, and *Salmonella enteritidis* ATCC 13,076 were adjusted to  $10^6$  CFU/mL. Minimum bactericidal

concentrations (MBC) were defined as the lowest extract concentration preventing visible growth on Mueller-Hinton Agar after 24 h at  $37\text{ }^{\circ}\text{C}$  [25]. The antibacterial activity of three different extracts was evaluated against *Staphylococcus aureus* ATCC 29,213, *Streptococcus mutans* ATCC 700,610, *Escherichia coli* ATCC 25,922, and *Salmonella enteritidis* ATCC 13,076 using the disk diffusion method. In the disk diffusion assay, sterile 6 mm paper disks were impregnated with 20  $\mu\text{L}$  of extract solution at a concentration of 500 ppm and carefully placed onto the surface of inoculated agar plates. Following incubation, the inhibition zone diameters formed around the disks were measured and recorded [26]. Bacterial cultures were incubated at  $37.5\text{ }^{\circ}\text{C}$  for 18 h and adjusted to approximately  $10^6$  CFU/mL with sterile saline. Extracts were dissolved in 10% DMSO with Tween 80 and filtered through a 0.45  $\mu\text{m}$  membrane. Ampicillin (25  $\mu\text{g}$ /disc) served as the positive control. After incubation, inhibition zones were measured with a caliper. All assays were conducted in triplicate, and results were calculated accordingly [19].

### Cytotoxicity Assays

The cytotoxicity of the extracts was evaluated on epithelial (L929) and cancer cell lines (HT-29, CaCo-2) using the MTT assay. Cells were maintained in DMEM at  $37\text{ }^{\circ}\text{C}$  with 5%  $\text{CO}_2$ . Absorbance was measured at 570 and 600 nm, and cell viability was expressed as a percentage relative to control wells [27].

### UV–Vis and Fluorescence Analysis

Stock solutions of metal ions (10 mM) were prepared in deionized water, including  $\text{Hg}^{2+}$ ,  $\text{Fe}^{3+}$ ,  $\text{Cu}^{2+}$ ,  $\text{Zn}^{2+}$ ,  $\text{Ni}^{2+}$ ,  $\text{Mn}^{2+}$ ,  $\text{Pb}^{2+}$ ,  $\text{Ag}^{+}$ ,  $\text{Al}^{3+}$ , and  $\text{Na}^{+}$ . Extract solutions (10 mg/mL) were diluted in phosphate buffer to 10  $\mu\text{g}$ /mL for spectroscopic measurements. UV–Vis spectra were recorded in the range of 200–800 nm. Fluorescence emission spectra were obtained after excitation at 260 nm, and emission intensity changes were monitored in the 480–800 nm region, particularly around 640–720 nm, where the most pronounced fluorescence responses were observed following metal ion addition. Measurements were performed at room temperature ( $\sim 25\text{ }^{\circ}\text{C}$ ) [27].

### Statistical Analysis

All experiments were performed using two independent biological replicates, and each analysis was conducted in triplicate as technical replicates ( $n=6$ ). Data were expressed as mean  $\pm$  standard deviation (SD). Statistical analyses were performed using SPSS 22.0 (IBM Corp., Armonk, NY,

USA). Prior to one-way ANOVA, normality and homogeneity of variance assumptions were evaluated. Significant differences between means were determined using Tukey's post hoc test at a significance level of  $p < 0.05$ . In all tables and figures, error bars represent standard deviation (SD).

## Results and Discussion

### Phenolic Content, Antioxidant Activity, and $\alpha$ -Glucosidase Inhibition of Extracts

In this study, the total phenolic content (TPC), free radical scavenging capacities (DPPH and ABTS), and  $\alpha$ -glucosidase inhibition activities of three *Teucrium* species (*T. orientale*, *T. polium*, and *T. turcicum*) were compared. The results revealed that *T. polium* exhibited the highest phenolic content (39.43 mg GAE/L), followed by *T. turcicum* (33.26 mg GAE/L) and *T. orientale* (7.22 mg GAE/L) (Table 1).

Regarding the DPPH radical scavenging capacity, *T. polium* ( $2.70 \pm 0.26$  mg/mL) and *T. turcicum* ( $3.02 \pm 0.09$  mg/mL) showed comparably high activities, whereas *T. orientale* ( $9.26 \pm 0.17$  mg/mL) was approximately threefold weaker. In the ABTS assay, *T. turcicum* ( $44.72 \pm 0.89$  mg/mL) demonstrated the lowest  $EC_{50}$  value, with *T. polium* ( $45.58 \pm 0.91$  mg/mL) not differing significantly ( $p > 0.05$ ) (Table 1). Species with higher phenolic content also exhibited stronger antioxidant capacities. Similarly, recent studies have emphasized the strong association between phenolic content and antioxidant activity in *Teucrium* species. For instance, Penumala et al. (2018) reported that *Teucrium* extracts rich in polyphenols displayed lower  $EC_{50}$  values and thus higher radical scavenging capacity [28]. Mihailović et al. (2020) demonstrated that environmental factors significantly affect phenolic profiles, thereby influencing antioxidant capacity [29]. The importance of phenolic richness as a key determinant of antioxidant potential has also been frequently highlighted in the literature [30, 31]. In particular, the high polyphenol content of *T. polium* has been attributed to its abundance of flavonoids and phenolic acids, which are known to enhance antioxidant activity [31]. Due to their rich phenolic and flavonoid composition, *Teucrium capitatum* extracts exhibit remarkable antioxidant and

antimicrobial activities, indicating their promising potential as natural bioactive agents [13].

With respect to  $\alpha$ -glucosidase inhibition, *T. polium* was again the most effective species ( $IC_{50}$ : 6.88 mg/mL). In contrast, *T. turcicum*, despite having a relatively high TPC value, exhibited weak inhibitory activity ( $IC_{50}$ : 26.9 mg/mL) (Table 1). This finding suggests that enzyme inhibition is determined not only by the total phenolic content but also by the qualitative diversity of phenolics and the overall phytochemical composition of the extract. Indeed, previous studies have reported that luteolin, apigenin, and rosmarinic acid derivatives play critical roles in  $\alpha$ -glucosidase inhibition [32–34]. Studies conducted on *Teucrium montanum* have demonstrated that polyphenolic compounds, particularly flavonoids, exhibit notable antidiabetic potential through the inhibition of key metabolic enzymes [12]. This may explain the poor inhibitory activity of *T. turcicum* despite its relatively high phenolic content.

Overall, *T. polium* stood out with its high TPC, strong radical scavenging activity, and pronounced  $\alpha$ -glucosidase inhibition. *T. orientale* exhibited limited biological activity due to its low phenolic content, whereas *T. turcicum* showed moderate antioxidant activity but weak enzyme inhibition despite its phenolic richness. These differences highlight the importance of species-specific phytochemical profiles. Recent phytochemical studies have confirmed that geographic variation, growing conditions, and extraction methods significantly influence the biological activity of *Teucrium* species [29, 35]. The present findings indicate that *T. polium* is a promising source in terms of both antioxidant capacity and  $\alpha$ -glucosidase inhibition, supporting its potential application as a functional food ingredient or natural antidiabetic agent.

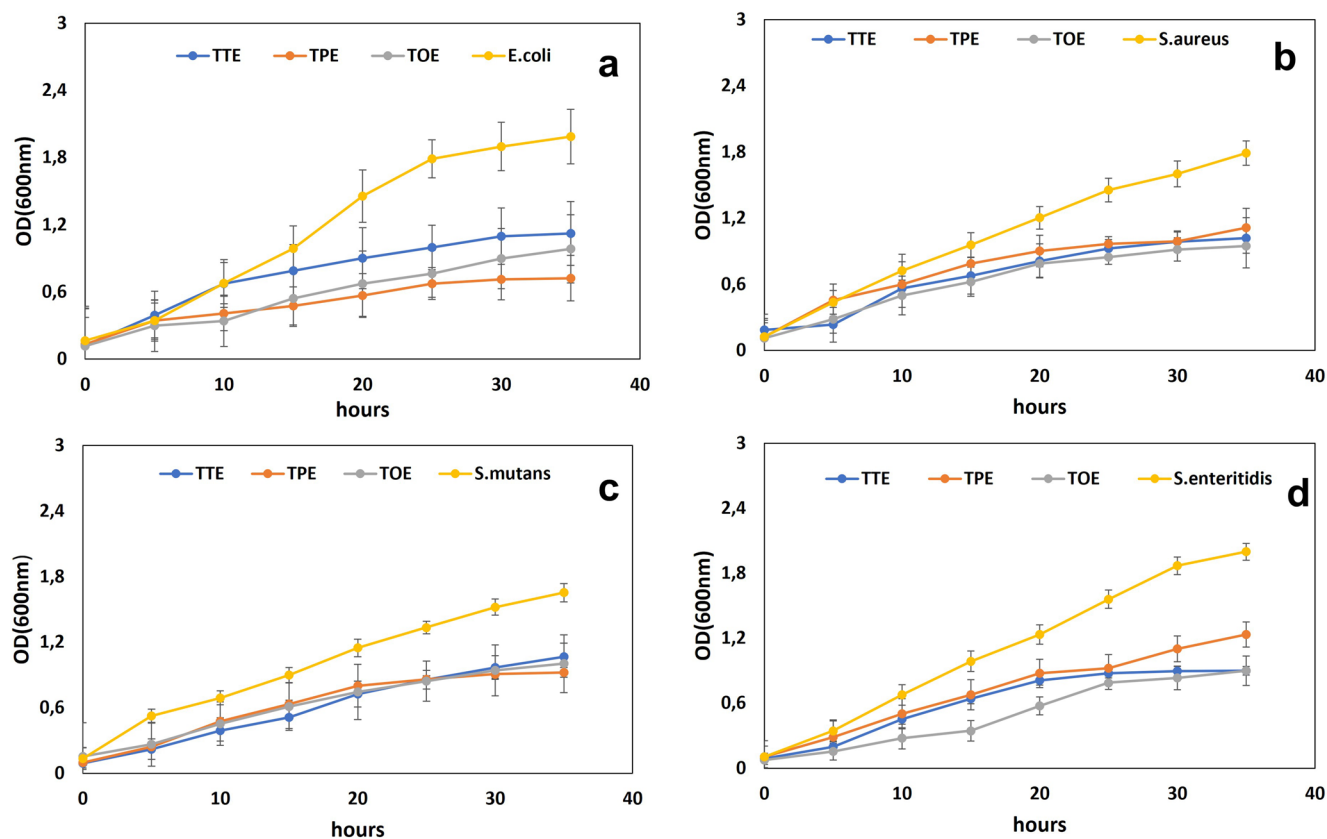
### Antibacterial Activity of Extracts

The antibacterial activities of *Teucrium* extracts against four bacterial strains (*E. coli*, *S. aureus*, *S. mutans*, and *S. enteritidis*) were evaluated by monitoring bacterial growth kinetics over 36 h (Fig. 1). The results revealed clear differences among the extracts. For *E. coli*, growth was significantly inhibited by *T. polium* (TPE) and *T. turcicum* (TTE), whereas *T. orientale* (TOE) showed weaker inhibition. In the case of

**Table 1** TPC, antioxidant and enzyme inhibition activity of extracts

| Sample   | Total Phenolic Content (mg GAE/L) | $EC_{50}$ of DPPH scavenging capacity (mg/mL) | $EC_{50}$ of ABTS scavenging capacity (mg/mL) | $IC_{50}$ of $\alpha$ -glucosidase inhibition (mg/mL) |
|----------|-----------------------------------|-----------------------------------------------|-----------------------------------------------|-------------------------------------------------------|
| TOE      | $7.22^b \pm 0.49$                 | $9.26^a \pm 0.17$                             | $57.86^a \pm 2.89$                            | $18.2^b \pm 0.14$                                     |
| TPE      | $39.43^a \pm 0.06$                | $2.70^b \pm 0.26$                             | $45.58^b \pm 0.91$                            | $6.88^c \pm 0.13$                                     |
| TTE      | $33.26^a \pm 0.40$                | $3.02^b \pm 0.09$                             | $44.72^b \pm 0.89$                            | $26.9^a \pm 0.12$                                     |
| Acarbose |                                   |                                               |                                               | $0.30^d \pm 0.02$                                     |

Mean  $\pm$  standard deviation (SD). Values with different uppercase superscript letters indicate significant differences ( $p < 0.05$ ). TOE (*Teucrium orientale* extract), TPE (*Teucrium polium* extract), TTE (*Teucrium turcicum* extract)



**Fig. 1** Time-dependent influence of the extracts on pathogen growth and development (TOE: *Teucrium orientale* extract, TPE: *Teucrium polium* extract, TTE: *Teucrium turcicum* extract)

*S. aureus*, both TPE and TTE markedly suppressed bacterial proliferation, while TOE exhibited moderate inhibition. Against *S. mutans*, TPE and TTE again exerted comparable inhibitory effects, whereas TOE remained the least effective. *S. enteritidis* was the most resistant strain, yet TPE still demonstrated measurable inhibitory activity, followed by TTE and TOE. Overall, the antibacterial potential of the extracts followed the order: TPE > TTE > TOE, consistently across all tested microorganisms.

In this study, extracts inhibited the growth of four different gram-positive and negative pathogens. Overall, the inhibition zone of common pathogens varied from 24.55 to 43.44 mm in diameter. Each extract caused an average inhibition zone of 25.00 to 30.00 mm in diameter (mm) in all pathogens. This indicated that all the extracts exhibited a significantly important ( $p < 0.05$ ) (Table 2).

The apparent differences observed between growth kinetic analyses and disk diffusion assays may be associated with methodological variations between the two techniques. Disk diffusion results are influenced by the diffusion capacity, polarity, and molecular size of phytochemical constituents within agar media, whereas growth kinetic

**Table 2** Antimicrobial activities of extracts (inhibition zone of growth in pathogens, mm)

| Sample   | E.coli                     | S.aureus                  | S. enteritidis            | S. mutans                 |
|----------|----------------------------|---------------------------|---------------------------|---------------------------|
| TOE      | 28.04 <sup>b</sup> ± 1.82  | 31.31 <sup>b</sup> ± 1.82 | 37.64 <sup>b</sup> ± 1.40 | 43.44 <sup>b</sup> ± 1.40 |
| TPE      | 26.67 <sup>bc</sup> ± 1.87 | 27.15 <sup>c</sup> ± 1.98 | 38.62 <sup>b</sup> ± 1.92 | 36.57 <sup>c</sup> ± 1.42 |
| TTE      | 24.55 <sup>c</sup> ± 1.24  | 32.32 <sup>b</sup> ± 1.76 | 31.33 <sup>c</sup> ± 1.35 | 40.83 <sup>b</sup> ± 1.31 |
| Amplisin | 74.60 <sup>a</sup> ± 2.34  | 71.11 <sup>a</sup> ± 2.45 | 70.20 <sup>a</sup> ± 1.15 | 69.12 <sup>a</sup> ± 1.52 |

Mean ± standard deviation (SD). Values with different uppercase superscript letters indicate significant differences ( $p < 0.05$ ). TOE (*Teucrium orientale* extract), TPE (*Teucrium polium* extract), TTE (*Teucrium turcicum* extract)

measurements reflect the direct inhibitory effects of extracts in liquid culture systems. Therefore, extracts exhibiting limited diffusion in agar may still demonstrate considerable antibacterial activity in broth-based kinetic analyses. In addition, differences in bacterial membrane permeability and extract viscosity may contribute to the observed variations between the methods. These findings are in line with recent studies reporting the broad-spectrum antimicrobial properties of *Teucrium* species, which are often attributed to their rich content of flavonoids, phenolic acids, and diterpenoids [31, 36]. Specifically, *T. polium* has been highlighted

as one of the most potent species in terms of antimicrobial efficacy, showing activity against both Gram-positive and Gram-negative bacteria [32, 37]. The greater activity of TPE compared with TTE and TOE may be associated with its higher total phenolic content and the presence of bioactive compounds such as apigenin and luteolin derivatives, which have been reported to disrupt bacterial membranes and inhibit key metabolic pathways [30, 34]. Notably, the relative resistance of *S. enteritidis* observed here is consistent with previous reports, as Gram-negative pathogens with complex outer membranes often exhibit reduced susceptibility to plant-derived extracts compared to Gram-positive bacteria [29]. The ethanolic extract of *Teucrium polium* exhibited moderate antibacterial activity against both Gram-positive and Gram-negative bacteria [38].

### Cytotoxic Effects of Extracts on Colorectal Cancer Cell Lines

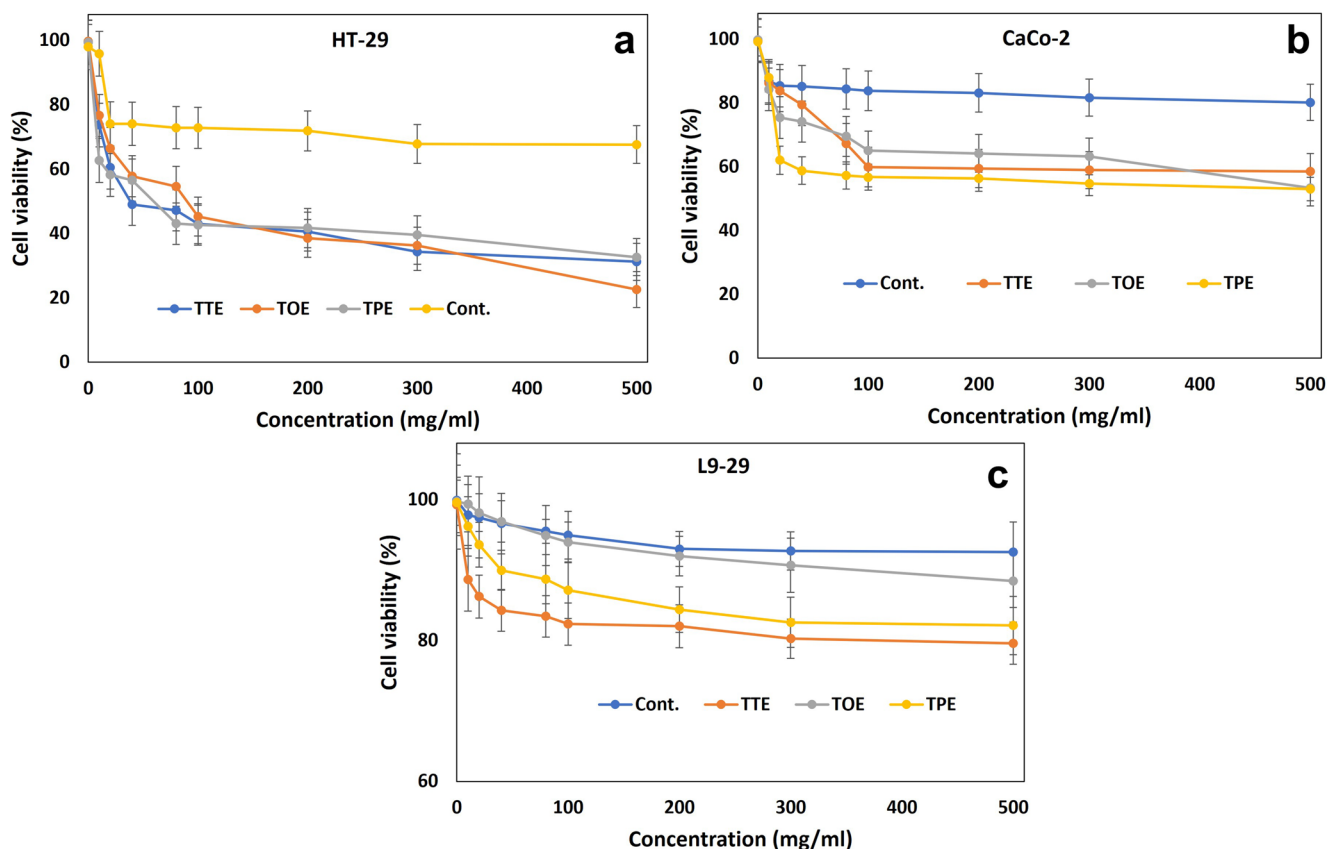
The cytotoxic effects of *T. orientale* (TOE), *T. polium* (TPE), and *T. turcicum* (TTE) extracts were evaluated against two human colorectal cancer cell lines (HT-29 and CaCo-2)

and one normal fibroblast line (L929) using concentration-dependent assays (Fig. 2,a–c).

In HT-29 cells, all extracts induced a marked reduction in cell viability in a dose-dependent manner. At 200  $\mu\text{g/mL}$ , viability decreased to approximately 40–50% for TPE and TTE, whereas TOE demonstrated a slightly weaker effect. At the highest concentration (400  $\mu\text{g/mL}$ ), TPE and TTE reduced viability to nearly 30%, while TOE retained viability above 40%. These findings suggest that TPE and TTE possess stronger antiproliferative potential against HT-29 cells.

In CaCo-2 cells, the extracts exerted even more pronounced cytotoxicity. Viability dropped below 40% with TPE and TTE at 200  $\mu\text{g/mL}$ , and below 30% at 400  $\mu\text{g/mL}$ . TOE showed intermediate inhibition, reducing viability to  $\sim 35$ –40% at the highest dose. Importantly, CaCo-2 cells appeared more sensitive to treatment than HT-29 cells, which is consistent with previous studies reporting variability in *Teucrium*-induced cytotoxic responses among different colorectal cancer cell lines [31, 32].

In contrast, L929 normal fibroblasts exhibited comparatively higher tolerance to the extracts. Even at 400  $\mu\text{g/mL}$ , cell viability remained above 70% for all treatments, with



**Fig. 2** Cell viability percentages of HT-29 (a), CaCo-2 (b), and L929 (c) cells obtained from cytotoxicity analysis (TOE: *Teucrium orientale* extract, TPE: *Teucrium polium* extract, TTE: *Teucrium turcicum* extract)

TPE causing the most noticeable decline (~72%), followed by TTE and TOE (Fig. 2). These findings suggest that the extracts may exert relatively greater cytotoxic effects on malignant cells than on normal fibroblast cells under the tested in vitro conditions. The IC<sub>50</sub> values calculated for HT-29 cells were 178.4 µg/mL for TPE, 192.6 µg/mL for TTE, and 261.3 µg/mL for TOE, whereas the corresponding IC<sub>50</sub> values for CaCo-2 cells were 134.8 µg/mL, 148.5 µg/mL, and 207.4 µg/mL, respectively (Table 3). These findings indicate concentration-dependent cytotoxic effects of the extracts against colorectal cancer cell lines under in vitro conditions.

These findings are consistent with previous studies reporting the cytotoxic potential of *Teucrium* species against colorectal cancer cells. Previous investigations have suggested that these effects may be associated with oxidative stress and apoptosis-related pathways. However, since the present study was limited to MTT-based viability analysis, further mechanistic investigations are required to clarify the underlying cell death mechanisms. For instance, Khodaei et al. (2018) reported that *T. polium* methanolic extract reduces HT-29 viability (IC<sub>50</sub> ≈ 3 µg/mL) by increasing ROS production, inducing mitochondrial membrane potential collapse, and upregulating SIRT3 activity [39]. Furthermore, essential oils derived from *T. polium* have demonstrated pronounced apoptotic and antiproliferative effects on colon cancer lines, such as CACO-2 (IC<sub>50</sub> ≈ 52.7 µg/mL), likely due to their rich sesquiterpene and flavonoid composition [40]. More recently, *Teucrium*-derived essential oils—particularly from *T. alopecurus*—were shown to trigger ROS generation, activate caspase-3/-8/-9, and induce PARP cleavage in HCT-116 colon cancer cells, suppressing tumorigenic gene expression and showing no toxicity in vivo [41]. In a broader context, essential oils have attracted attention in colorectal cancer research due to their reported in vitro cytotoxic effects, including the induction of apoptosis, modulation of the cell cycle, and potential inhibition of metastatic processes, suggesting their possible relevance for further investigation as supportive bioactive compounds [42].

**Table 3** IC<sub>50</sub> values of *Teucrium* extracts in HT-29, CaCo-2, and L929 cells

| Sample | Cytotoxicity (IC <sub>50</sub> , µg/mL) |                           |      |
|--------|-----------------------------------------|---------------------------|------|
|        | HT-29                                   | CaCo-2                    | L929 |
| TPE    | 178.4 <sup>a</sup> ± 1.03               | 134.8 <sup>a</sup> ± 0.33 | N.D  |
| TTE    | 192.6 <sup>b</sup> ± 0.37               | 148.5 <sup>b</sup> ± 0.81 | N.D  |
| TOE    | 261.3 <sup>a</sup> ± 1.52               | 207.4 <sup>a</sup> ± 1.28 | N.D  |

N.D.: Not determined because cell viability did not decrease below 50% within the tested concentration range. mean ± standard deviation (SD). Values with different uppercase superscript letters indicate significant differences ( $p < 0.05$ ). TOE (*Teucrium orientale* extract), TPE (*Teucrium polium* extract), TTE (*Teucrium turcicum* extract)

## Detection of Hg<sup>2+</sup> and Cu<sup>2+</sup> ions by Fluorescent Spectral Studies

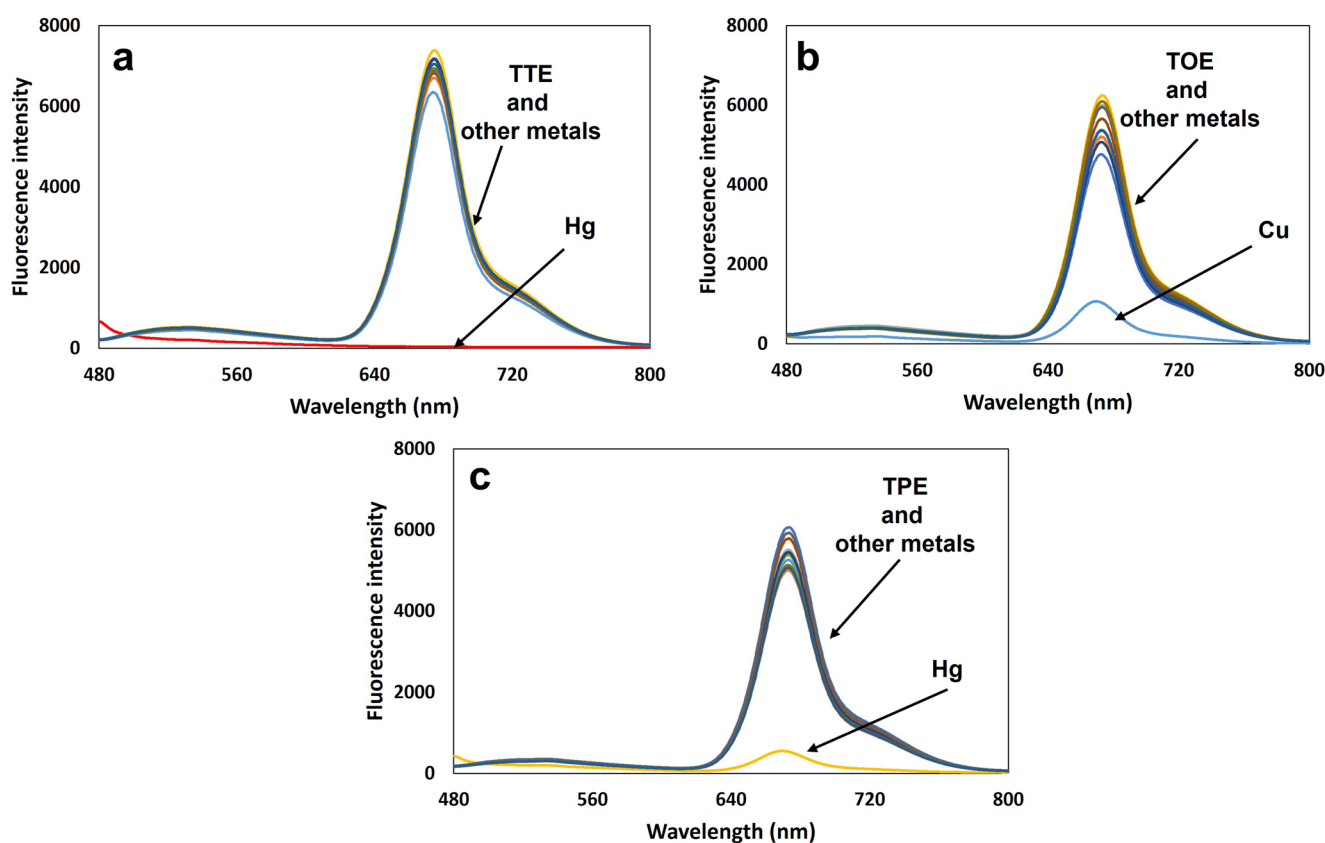
The interaction and detection potential of the phenolic extracts (TTE, TOE, and TPE) with various metal cations were evaluated using fluorescence spectral analysis (Fig. 3). The fluorescence emission profiles of the extracts were monitored in the 480–800 nm range, where distinct emission bands were observed around 670–690 nm. Significant fluorescence quenching responses were detected particularly in the 640–720 nm region after interaction with specific metal ions.

The influence of varying concentrations of Hg<sup>2+</sup> and Cu<sup>2+</sup> ions on the fluorescence emission behavior of the extracts was further investigated (Fig. 4). TOE extract exhibited a pronounced “turn-off” fluorescence response in the presence of Cu<sup>2+</sup> ions, whereas TTE and TPE showed strong fluorescence quenching upon exposure to Hg<sup>2+</sup> ions. This fluorescence suppression indicates the high sensitivity of the extracts toward their corresponding metal ions and highlights their potential for selective metal detection. Furthermore, titration studies demonstrated that increasing concentrations of the target ions resulted in progressive fluorescence quenching, confirming the strong affinity of TOE for Cu<sup>2+</sup> and TTE/TPE for Hg<sup>2+</sup> ions.

The fluorescence titration analysis demonstrated that the *Teucrium* extract–metal ion sensing systems exhibited good linearity ( $R^2 = 0.94–0.96$ ) within the concentration range of 0–10 µM. Among the tested systems, TTE–Hg<sup>2+</sup> showed the highest sensitivity with the steepest slope value ( $k = 660$ ) and the lowest detection limit (LOD = 0.10 µM). These findings indicate the potential applicability of the developed fluorescence sensing systems for sensitive metal ion detection (Table 4).

To evaluate the selectivity of the extracts, fluorescence competition experiments were performed. When 10 equivalents of various competing metal ions were added to solutions containing 5 equivalents of Hg<sup>2+</sup>, the fluorescence of TTE and TPE remained largely unaffected. Similarly, the addition of 10 equivalents of competing metal ions to solutions with Cu<sup>2+</sup> did not significantly alter the fluorescence response of TOE (Fig. 5). These findings suggest that the extracts preserve their selective responsiveness and binding affinity toward Hg<sup>2+</sup> and Cu<sup>2+</sup> ions even in the presence of other potentially interfering metals.

Food sensors function through the selective recognition of analytes related to food safety and quality, relying on specific chemical or biological interactions between recognition elements and target compounds [43]. In this context, phenolic-rich extracts such as TOE, TTE, and



**Fig. 3** Fluorescence spectra of (a) TTE, (b) TOE, (c) TPE (0.1  $\mu$ M) in the presence of various metal ions (20 equivalents each) (TOE: *Teucrium orientale* extract, TPE: *Teucrium polium* extract, TTE: *Teucrium turcicum* extract)

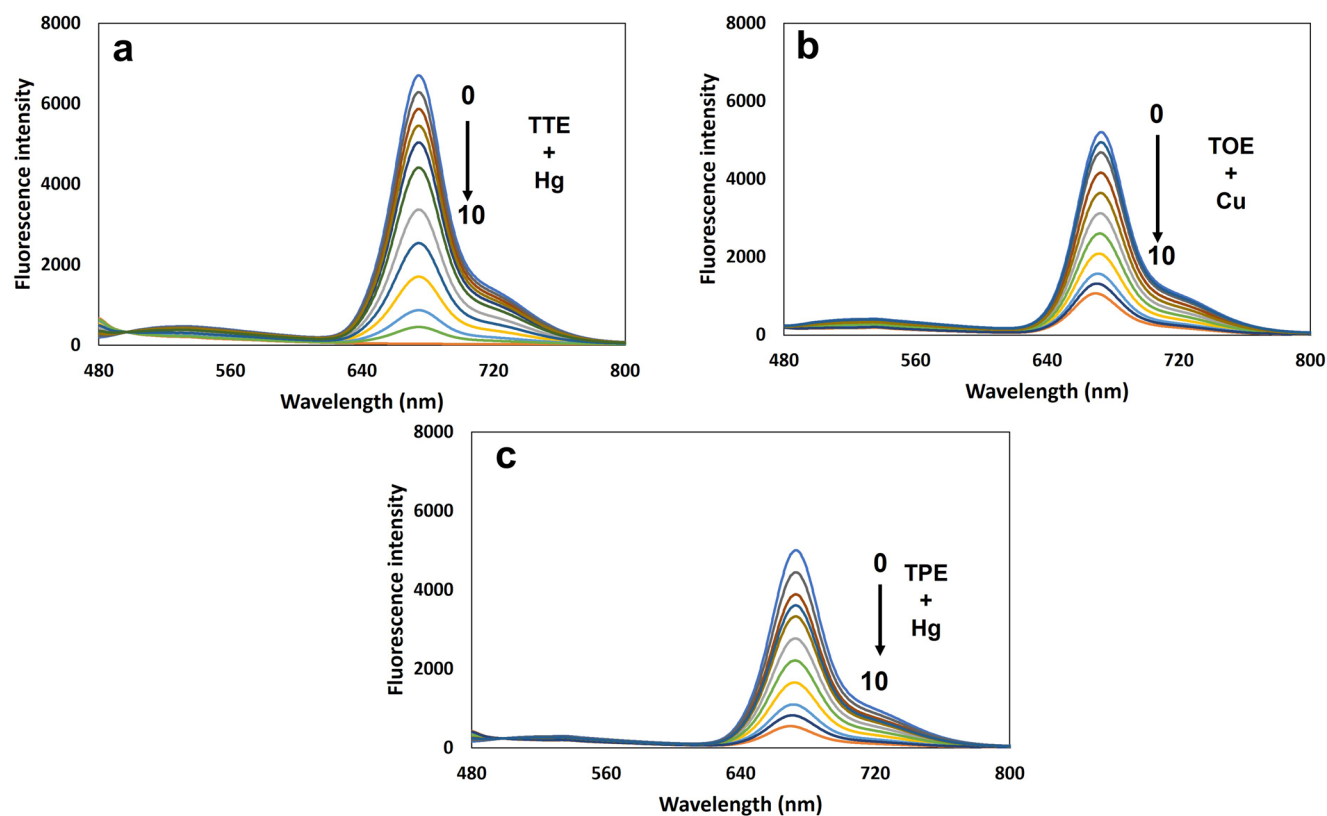
TPE demonstrate promising potential as recognition elements for heavy metal sensing. The hydroxyl and aromatic groups of phenolic compounds provide multiple coordination sites, enabling selective interactions with metal ions such as  $\text{Hg}^{2+}$  and  $\text{Cu}^{2+}$ . These intrinsic structural properties not only confer specificity and sensitivity but also ensure relative stability and safety in food-related applications. Consequently, the fluorescence quenching responses observed for TOE with  $\text{Cu}^{2+}$  and for TTE/TPE with  $\text{Hg}^{2+}$  can be attributed to their phenolic composition, highlighting their suitability as natural recognition elements in the design of food-safe optical sensors for heavy metal detection.

### Detection of $\text{Hg}^{2+}$ and $\text{Cu}^{2+}$ ions by the UV–vis Spectral Studies

The optical sensing ability of the investigated plant extracts toward  $\text{Hg}^{2+}$  and  $\text{Cu}^{2+}$  ions was systematically evaluated by UV–Vis spectroscopy. As depicted in Fig. 6, the intrinsic pigments, particularly phenolic constituents, imparted characteristic coloration to the extracts. Upon the addition of

$\text{Cu}^{2+}$ , a distinct absorption band emerged at approximately 600 nm, while  $\text{Hg}^{2+}$  induced a new band around 650 nm. These spectral and visible color transitions were exclusive to  $\text{Cu}^{2+}$  and  $\text{Hg}^{2+}$ , as no significant variations were detected with other tested metal ions ( $\text{Na}^+$ ,  $\text{Ag}^+$ ,  $\text{Al}^{3+}$ ,  $\text{Pb}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Mn}^{2+}$ ,  $\text{Ni}^{2+}$ ,  $\text{Zn}^{2+}$ ,  $\text{Fe}^{2+}$ ). For the TOE extract,  $\text{Cu}^{2+}$  addition resulted in a novel absorption signal at 600 nm, indicative of structural rearrangements, likely due to partial ring opening (Fig. 6b). Similarly, in the case of TTE and TPE extracts, the introduction of  $\text{Hg}^{2+}$  yielded a new peak at 650 nm (Fig. 6a and c). These observable shifts, accompanied by clear colorimetric responses (Fig. 6), underscore the potential of these extracts to act as “naked-eye” probes for  $\text{Cu}^{2+}$  and  $\text{Hg}^{2+}$  detection, with high selectivity and affinity [19].

To further elucidate the extract–metal interactions, UV–Vis titration experiments were performed for TOE, TTE, and TPE (Fig. 7). Progressive addition of  $\text{Cu}^{2+}$  to TOE consistently decreased absorbance intensity at 600 nm, while  $\text{Hg}^{2+}$  addition to TTE and TPE led to a systematic decline at 650 nm. These reproducible patterns confirm the stability of the complexation process and the robustness of the optical response.



**Fig. 4** Fluorescence response intensities of (a) TTE, (b) TOE, (c) TPE against distinct metal ions (1:20, v/v) (TOE: *Teucrium orientale* extract, TPE: *Teucrium polium* extract, TTE: *Teucrium turcicum* extract)

**Table 4** Analytical performance parameters of *Teucrium* extract–metal ion fluorescence sensing systems based on fluorescence titration analysis

| System                 | Linear equation    | $R^2$ | Slope (k) | LOD ( $\mu\text{M}$ ) | Linear range ( $\mu\text{M}$ ) |
|------------------------|--------------------|-------|-----------|-----------------------|--------------------------------|
| TPE - $\text{Hg}^{2+}$ | $y = -450x + 5000$ | 0.95  | 450       | 0.15                  | 0–10                           |
| TTE - $\text{Hg}^{2+}$ | $y = -660x + 6600$ | 0.96  | 660       | 0.10                  | 0–10                           |
| TOE - $\text{Cu}^{2+}$ | $y = -400x + 5100$ | 0.94  | 400       | 0.18                  | 0–10                           |

TOE (*Teucrium orientale* extract), TPE (*Teucrium polium* extract), TTE (*Teucrium turcicum* extract)

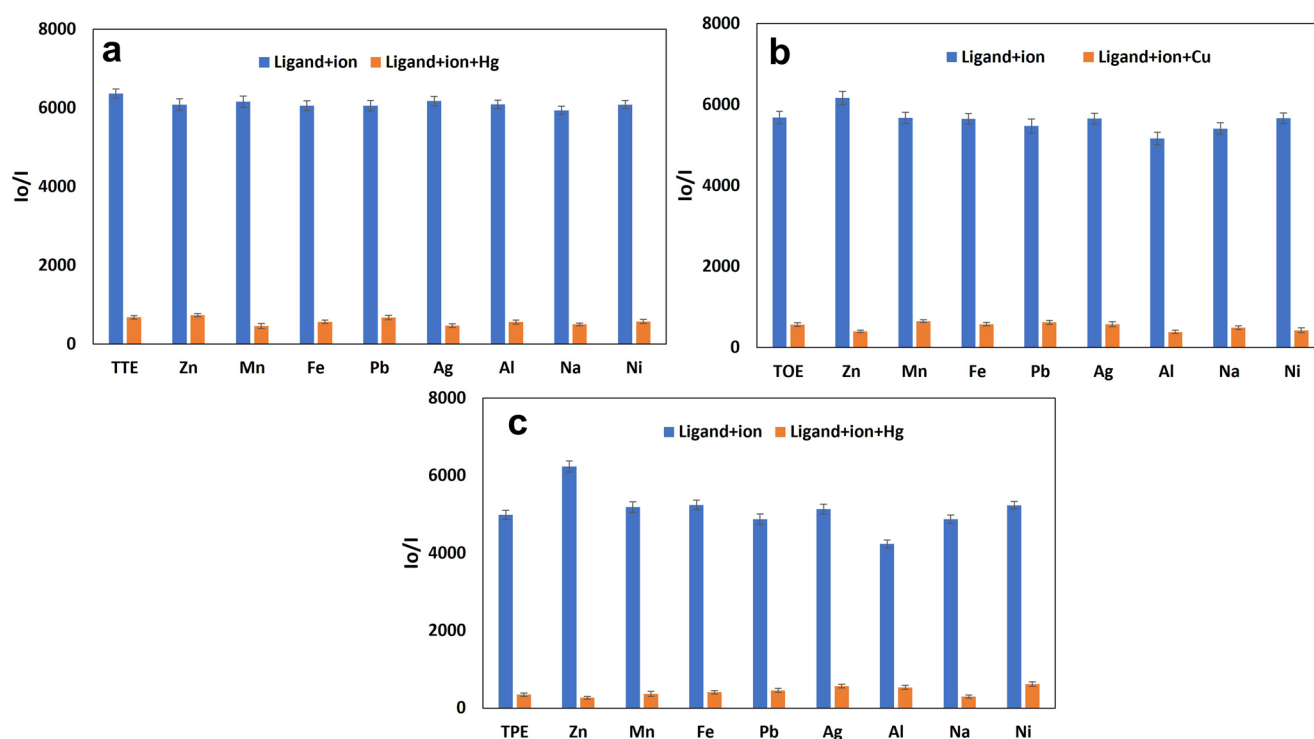
The binding stoichiometry was subsequently probed via Job's method of continuous variation (Fig. 8). Across all extracts (TOE– $\text{Cu}^{2+}$ , TTE– $\text{Hg}^{2+}$ , and TPE– $\text{Hg}^{2+}$ ), maximum absorbance was recorded at a mole fraction of 0.5, demonstrating a 1:1 binding ratio between extract molecules and the target ions. This outcome provides strong evidence of well-defined coordination interactions, positioning the extracts as promising ligands for selective metal sensing (Fig. 8).

The FTIR spectra demonstrated noticeable spectral changes after interaction of the *Teucrium* extracts with

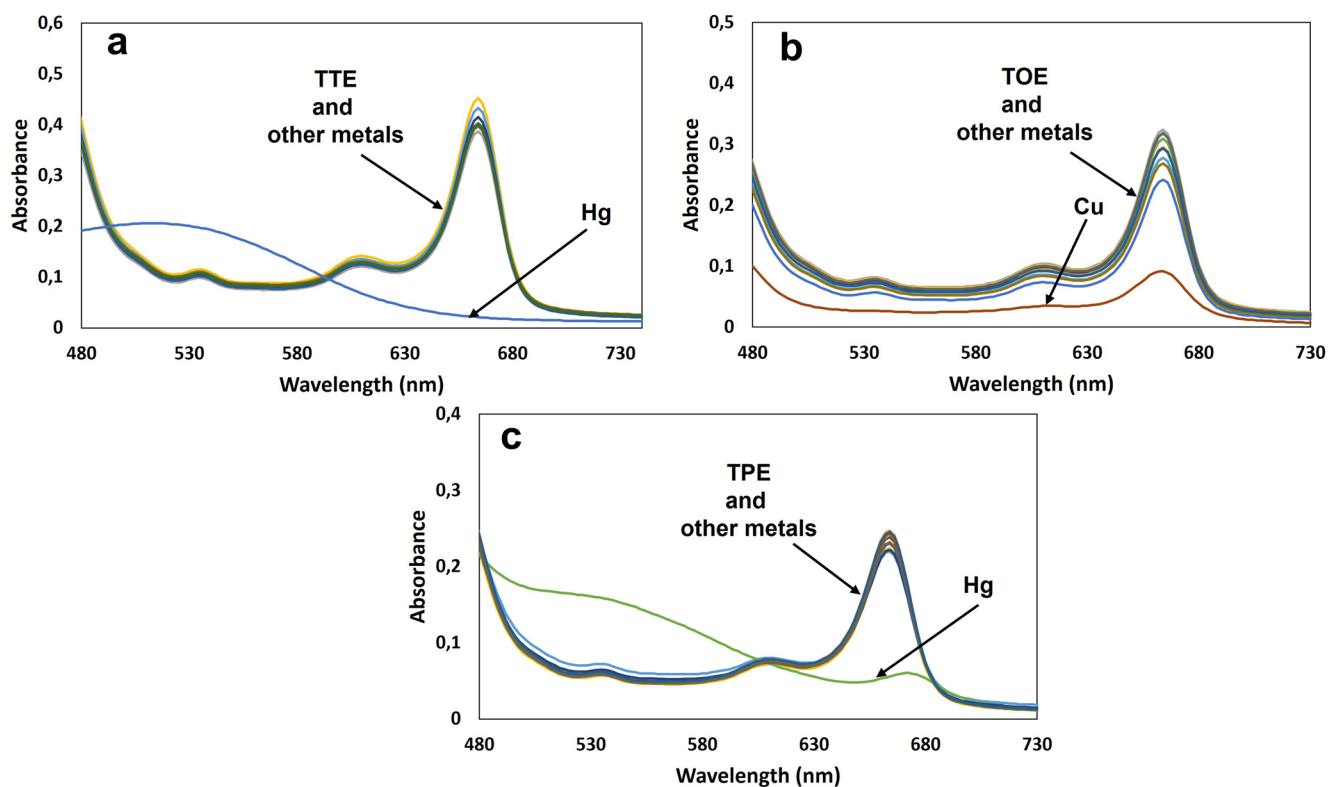
$\text{Hg}^{2+}$  and  $\text{Cu}^{2+}$  ions, indicating the involvement of oxygen-containing functional groups in metal coordination. In particular, broadening and intensity variations observed in the O–H stretching region ( $3200\text{--}3400\text{ cm}^{-1}$ ) suggest the participation of hydroxyl groups associated with phenolic compounds. In addition, spectral alterations in the  $1600\text{--}1400\text{ cm}^{-1}$  region may be attributed to C=O and aromatic C=C vibrations, while changes detected between  $1200$  and  $1000\text{ cm}^{-1}$  indicate the contribution of C–O stretching vibrations to the coordination process.

These findings suggest that phenolic constituents containing hydroxyl and ortho-dihydroxyl aromatic structures may play an important role in stabilizing extract–metal complexes through chelation interactions. Similar coordination behavior has previously been reported for plant-derived phenolic–metal complexes, where oxygen donor groups act as primary metal-binding sites. Therefore, the observed FTIR modifications support the proposed fluorescence quenching and metal-binding mechanisms of the *Teucrium* extract systems (Fig. 9).

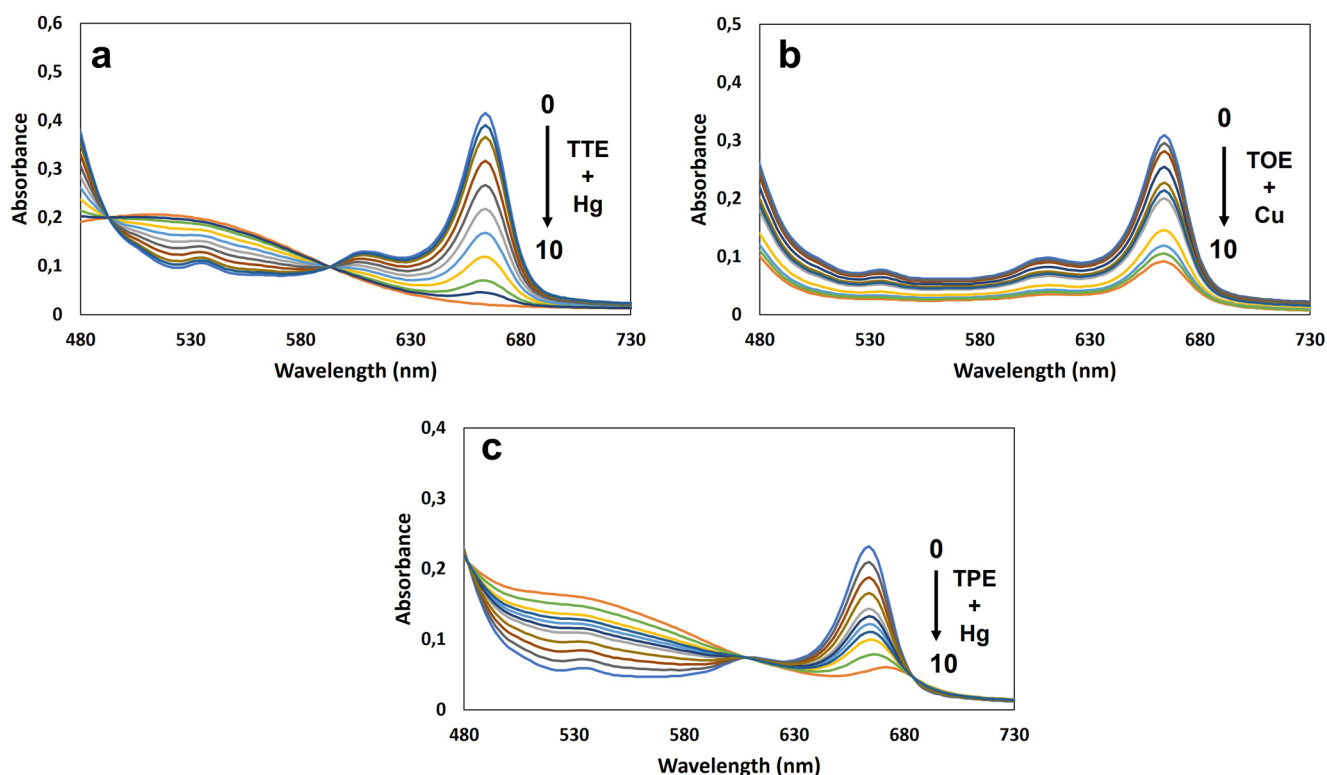
In the region of  $1700\text{--}1500\text{ cm}^{-1}$ , the bands are attributed to the aromatic C = C vibrations of phenolic rings



**Fig. 5** Impact of competing ions on the fluorescence intensity at 320 nm for extract- $\text{Hg}^{2+}/\text{Cu}^{2+}$  complexes (TOE: *Teucrium orientale* extract, TPE: *Teucrium polium* extract, TTE: *Teucrium turcicum* extract)



**Fig. 6** UV-Vis spectral analysis of (a) TTE, (b) TOE, (c) TPE (0.1  $\mu\text{M}$  in phosphate buffer) in the presence of metal ions (TOE: *Teucrium orientale* extract, TPE: *Teucrium polium* extract, TTE: *Teucrium turcicum* extract)



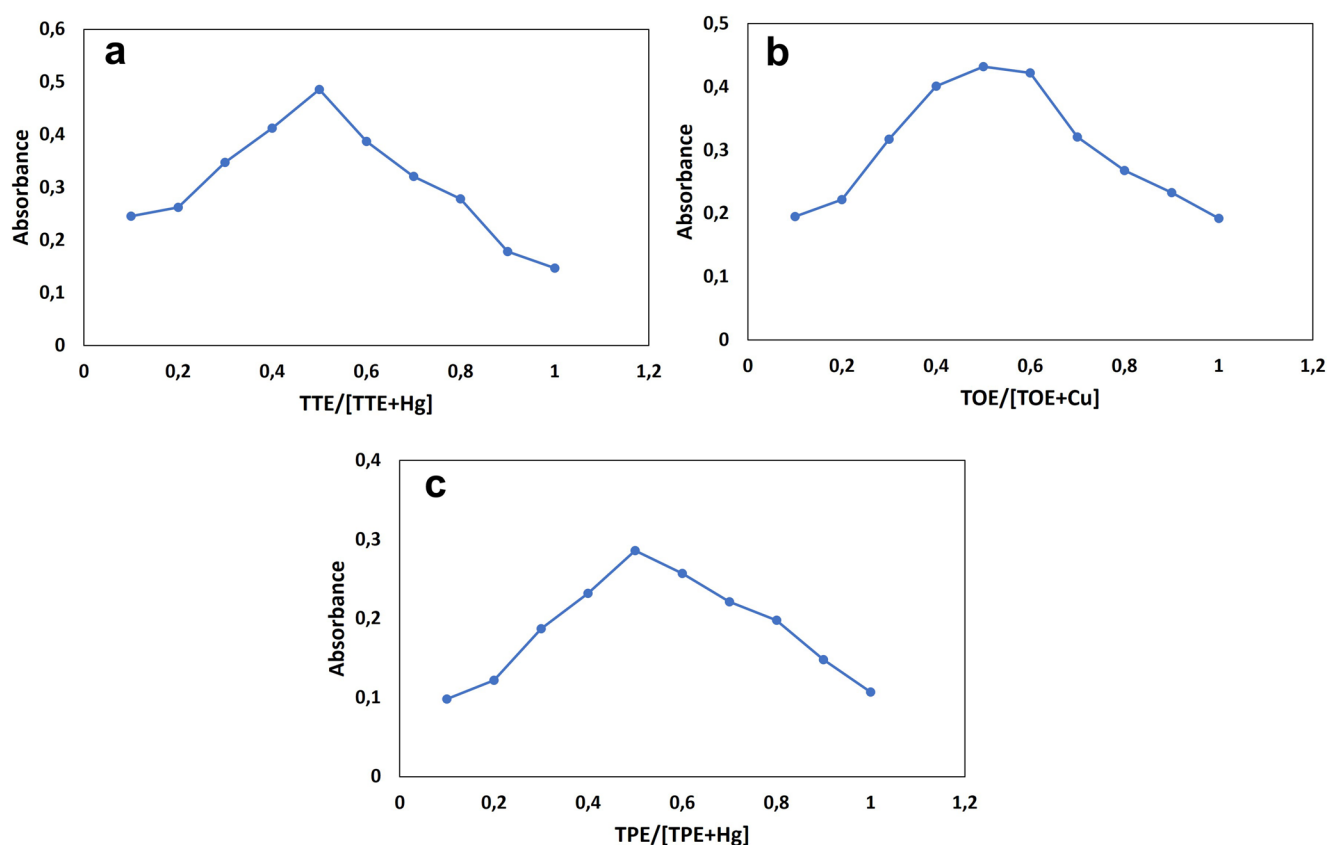
**Fig. 7** UV–Vis absorption changes of (a) TTE, (b) TOE, (c) TPE upon varying  $\text{Hg}^{2+}/\text{Cu}^{2+}$  concentrations (0–10 v/v) (TOE: *Teucrium orientale* extract, TPE: *Teucrium polium* extract, TTE: *Teucrium turcicum* extract)

and, to some extent, to carbonyl groups. Upon addition of metal ions, shifts and intensity variations were observed in this region, suggesting that aromatic  $\pi$ -electron systems also participate in the interaction with metal ions. Thus, not only hydroxyl groups but also phenolic rings contribute to the metal-binding process. Furthermore, shifts were detected in the  $1300\text{--}1000\text{ cm}^{-1}$  region, which corresponds to C–O stretching vibrations. This finding supports the involvement of C–O bonds within phenolic structures in metal coordination [44, 45]. In the fingerprint region ( $< 800\text{ cm}^{-1}$ ), the appearance of new bands and changes in the intensity of existing ones further demonstrated that complexation induced structural rearrangements in the overall vibrational framework of the molecules. In conclusion, the FTIR results clearly demonstrate that TPE, TOE, and TTE samples interact with  $\text{Hg}^{2+}$  and  $\text{Cu}^{2+}$  ions, forming strong complexes through phenolic –OH groups and aromatic structures. The ability of phenolic groups to establish coordination bonds with metal ions highlights the potential of these structures as effective metal chelators and biologically relevant complexing agents.

## Conclusions

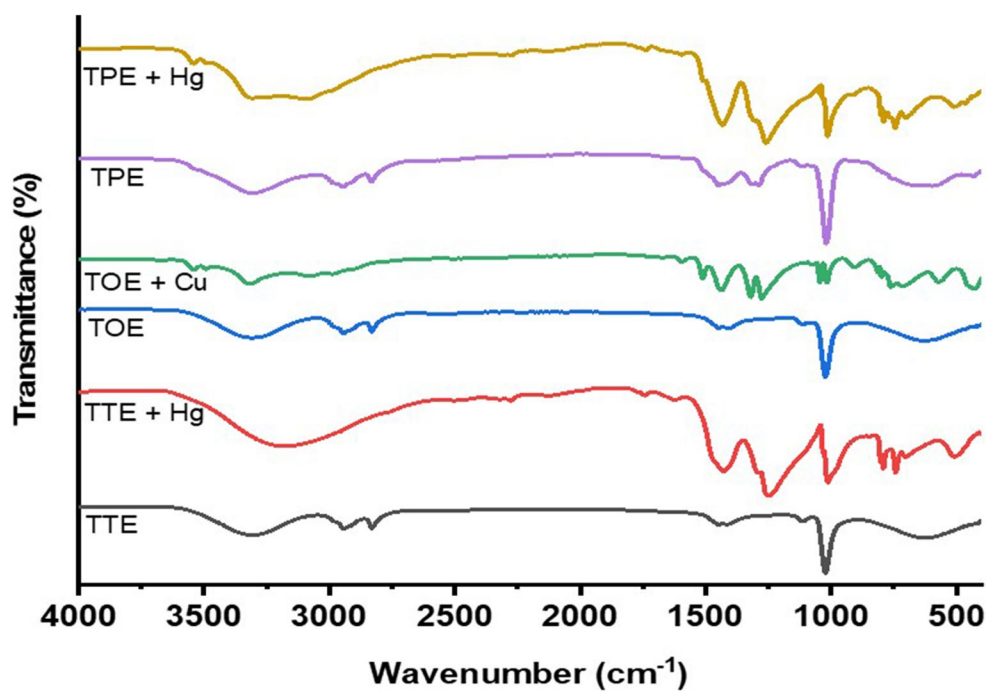
The present study comparatively evaluated the phytochemical composition, biological activities, and metal-binding properties of *Teucrium polium*, *Teucrium orientale*, and *Teucrium turcicum* extracts. Among the tested species, *T. polium* exhibited the highest phenolic content together with notable antioxidant,  $\alpha$ -glucosidase inhibitory, and antibacterial activities. In vitro cytotoxicity assays demonstrated that the extracts reduced the viability of HT-29 and CaCo-2 colorectal cancer cells while showing comparatively lower toxicity toward normal fibroblast cells.

In addition to their biological activities, the investigated extracts displayed selective metal-binding behavior toward  $\text{Hg}^{2+}$  and  $\text{Cu}^{2+}$  ions, as confirmed by fluorescence quenching, UV–Vis analyses, and 1:1 binding stoichiometry. To the best of our knowledge, this is the first comparative study reporting the metal ion interaction and sensing-related properties of these *Teucrium* species. Overall, the findings suggest that phenolic-rich *Teucrium* extracts may represent promising natural materials for further investigation in bioactive and spectroscopic sensing-related applications.



**Fig. 8** Job's plot representation for (a) TTE, (b) TOE, (c) TPE systems (TOE: *Teucrium orientale* extract, TPE: *Teucrium polium* extract, TTE: *Teucrium turcicum* extract)

**Fig. 9** FTIR spectral interpretation of extract–metal ion complexes (a) TTE, (b) TOE, (c) TPE (TOE: *Teucrium orientale* extract, TPE: *Teucrium polium* extract, TTE: *Teucrium turcicum* extract)



**Author Contributions** Hülya Şen Arslan: Conceptualization; Investigation; Funding acquisition; Writing—original draft; Validation; Visualization; Data curation; Bahar Yılmaz Altınok: Formal analysis; Investigation; Methodology; Analysis, Writing—review & editing. Ömer Çeçen: Resources.

**Funding** This research received no external funding.

**Data Availability** All data generated or analysed during this study are included in this published article.

## Declarations

**Ethics Approval** Ethics approval was not required for this study.

**Competing interests** The authors declare no competing interests.

## References

1. R.G. Candela, S. Rosselli, M. Bruno, G. Fontana, A review of the phytochemistry, traditional uses and biological activities of the essential oils of genus *Teucrium*. *Planta Med.* **87**(06), 432–479 (2020)
2. S. Selvi, R. Polat, U. Çakılcioglu, F. Celep, T. Dirmenci, Z.F. Ertuğ, An ethnobotanical review on medicinal plants of the *Lamiaceae* family in Turkey. *Turkish J. Bot.* **46**(4), 283–332 (2022)
3. Ç. Çeçen, T. Özcan, A new *Teucrium* L. (*Lamiaceae*) species from South Anatolia (Turkey). *Turk. J. Bot.* **45**, 353–370 (2021)
4. E. Deveci, G. Tel-Çayan, F. Çayan, B. Yılmaz Altınok, S. Aktaş, Chemical characterization, in vitro antioxidant, anti-cancer and enzyme inhibition activities of three edible mushroom species. *J. Food Meas. Charact.* **17**(5), 5518–5533 (2023)
5. F. Bray, J. Ferlay, I. Soerjomataram, R.L. Siegel, L.A. Torre, A. Jemal, Global cancer statistics 2018: GLOBOCAN estimates of incidence and mortality worldwide for 36 cancers in 185 countries. *CA Cancer J. Clin.* **68**(6), 394–424 (2018)
6. T.L. Jorgensen, J. Hallas, S. Friis, J. Herrstedt, Comorbidity in elderly cancer patients in relation to overall and cancer-specific mortality. *Br. J. Cancer* **106**(7), 1353–1360 (2012)
7. A.G. Gutiérrez-Rodríguez, C. Juárez-Portilla, T. Olivares-Banuelos, R.C. Zepeda, Anticancer activity of seaweeds. *Drug Discovery Today* **23**(2), 434–447 (2018)
8. H. Şen, Arslan, Eco-friendly microwave-assisted extraction of fruit and vegetable peels demonstrates great biofunctional properties. *Food Sci. Nutr.* **2024**, 12:8930–8938 (2024)
9. D. Pádua, E. Rocha, D. Gargiulo, A.A. Ramos, Bioactive compounds from brown seaweeds: Phloroglucinol, fucoxanthin and fucoidan as promising therapeutic agents against breast cancer. *Phytochem. Lett.* **14**, 91–98 (2015)
10. U. Cornelli, G. Belcaro, M. Recchia, A. Finco, Levothyroxine and lung cancer in females: the importance of oxidative stress. *Reprod. Biol. Endocrinol.* **11**, 1–6 (2013)
11. Y. Pan, Mitochondria, reactive oxygen species, and chronological aging: a message from yeast. *Exp. Gerontol.* **46**(11), 847–852 (2011)
12. P. Sailović, B. Odžaković, D. Bodroža, J. Vulić, J. Čanadanović-Brunet, J. Zvezdanović, B. Danilović, Polyphenolic composition and antimicrobial, antioxidant, anti-inflammatory, and antihyperglycemic activity of different extracts of *Teucrium montanum* from Ozren Mountain. *Antibiotics* **13**(4), 358 (2024)
13. R. Tarik, A. Dríoiche, J. El Amri, M. Ed-Dahmouny, A. Shahat, N. Hadi, A.A. Shahat, M. Aicha, H. Nadia, F. El Makhoukhi, A. El Ouali Lalami, N. Elmoulaj, E. Bruno, H. Lhoussain, T. Zair, Phytochemical profiling and bioactivity assessment of *Teucrium capitatum* L. essential oil and extracts: experimental and in silico insights. *Pharmaceuticals* **17**(12), 1578 (2024)
14. W. Kooti, K. Servatyari, M. Behzadifar, M. Asadi-Samani, F. Sadeghi, B. Nouri, H. Zare Marzouni, Effective medicinal plant in cancer treatment, Part 2: review study. *J. Evid. Based Complement. Altern. Med.* **22**(4), 982–995 (2017)
15. H. Sharma, L. Parihar, P. Parihar, Review on cancer and anticancerous properties of some medicinal plants. *J. Med. Plant. Res.* **5**, 1818–1835 (2011)
16. N. Xia, S. Liang, D. Deng, Y. Chang, X. Yi, Metal–phenolic networks for sensing applications. *Biosensors* **15**(9), 600 (2025)
17. Y. Gao, J. He, X. Li, J. Li, H. Wu, H. Wen, T. Li, J. Hao, J. Yoon, Fluorescent chemosensors facilitate the visualization of plant health and their living environment in sustainable agriculture. *Chem. Soc. Rev.* **53**, 6992–7090 (2024)
18. K. Kaymaz, H. Şen Arslan, B. Yılmaz Altınok, Functional potential of Valeriana extracts: Spectroscopic characterization, biological activities and heavy metal monitoring. *Spectrochim. Acta Part A Mol. Biomol. Spectrosc.* **127045** (2026)
19. H. Şen Arslan, B. Yılmaz Altınok, Functional properties of betalains: binding of Hg<sup>2+</sup> and Cu<sup>2+</sup> ions, sensor capabilities, and antimicrobial activity. *Int. J. Food Sci. Technol.* **60**(1), vvae069 (2025)
20. H. Şen Arslan, M. Çam, Antidiabetic and antioxidant properties of nine medicinal and aromatic plants extracts: Inhibition of key enzymes linked to type-2 diabetes. *J. Agroalimentary Processes Technol.* **28**(1) (2022)
21. M. Cam, N.C. Icyer, Phenolics of pomegranate peels: extraction optimization by central composite design and alpha glucosidase inhibition potentials. *J. Food Sci. Technol.* **52**, 1489–1497 (2015)
22. R. Fan, F. Yuan, N. Wang, Y. Gao, Y. Huang, Extraction and analysis of antioxidant compounds from the residues of *Asparagus officinalis* L. *J. Food Sci. Technol.* **52**, 2690–2700 (2015)
23. R.D.P.P. Fernandes, M.A. Trindade, F.G. Tonin, C.D.G. Lima, S.M.P. Pugine, P.E.S. Munekata, M.P. De Melo, Evaluation of antioxidant capacity of 13 plant extracts by three different methods: cluster analyses applied for selection of the natural extracts with higher antioxidant capacity to replace synthetic antioxidant in lamb burgers. *J. Food Sci. Technol.* **53**, 451–460 (2016)
24. G.J. McDougall, F. Shpiro, P. Dobson, P. Smith, A. Blake, D. Stewart, Different polyphenolic components of soft fruits inhibit  $\alpha$ -amylase and  $\alpha$ -glycosidase. *J. Agric. Food Chem.* **53**, 2760–2766 (2025)
25. R. Bayat, M. Akin, B. Yılmaz, M. Bekmezci, M. Bayrakci, F. Sen, Biogenic platinum based nanoparticles: synthesis, characterization and their applications for cell cytotoxic, antibacterial effect, and direct alcohol fuel cells. *Chem. Eng. J. Adv.* **14**, 100471 (2023)
26. H.B. Keskinaya, E. Deveci, B.Y. Altınok, N.E. Gümüş, E. Aslan, E. Ç. Akküz, Karakurt. HPLC-UV analysis of phenolic compounds and biological activities of *Padina pavonica* and *Zanardinia typus* marine macroalgae species. *Turkish J. Bot.* **47**, 231–243 (2023)
27. B. Yılmaz, M. Keskinates, M. Bayrakci, Novel integrated sensing system of calixarene and rhodamine molecules for selective colorimetric and fluorometric detection of Hg<sup>2+</sup> ions in living cells. *Spectrochim. Acta Part A Mol. Biomol. Spectrosc.* **245**, 118904 (2021)
28. M. Penumala, R.B. Zinka, J.B. Shaik, S.K.R. Mallepalli, R. Vadde, Amooru. Phytochemical profiling and in vitro screening for anticholinesterase, antioxidant, antiglycosidase and neuroprotective effect of three traditional medicinal plants for Alzheimer's Disease and Diabetes Mellitus dual therapy. *BMC Complement. Altern. Med.* **18**(1), 77 (2018)
29. V. Mihailović, J.S. Katanić Stanković, N. Mihailović, Phenolic compounds diversity of *Teucrium* species. *Teucrium species*:

- biology and applications* (143–177). Cham: Springer International Publishing (2020)
30. C.S. Rempe, K.P. Burris, S.C. Lenaghan, Jr Stewart, C. N. The potential of systems biology to discover antibacterial mechanisms of plant phenolics. *Front. Microbiol.* **8**, 422 (2017)
  31. Z. Sadeghi, J.L. Yang, A. Venditti, M. Moridi Farimani, A review of the phytochemistry, ethnopharmacology and biological activities of *Teucrium* genus (Germander). *Nat. Prod. Res.* **36**(21), 5647–5664 (2022)
  32. S. Bahramikia, P.H.H. Gavyar, R. Yazdanparast, *Teucrium polium* L: An updated review of phytochemicals and biological activities. *Avicenna J. Phytomedicine.* **12**(3), 224 (2022)
  33. J.Y. Lee, H.S. Lee, Y.Y. Lee, M.H. Kim, H.J. Kim, N. Han, Yeon. Comprehensive study on the inhibition mechanism of alpha-glucosidase by flavonoids via kinetic and structural analysis. *Biotechnol. Bioprocess Eng.* **29**(2), 413–425 (2024)
  34. D. Sarkar, A. Christopher, K. Shetty, Phenolic bioactives from plant-based foods for glycemic control. *Front. Endocrinol.* **12**, 727503 (2022)
  35. L. De Martino, R. Coppola, V. De Feo, L. Caputo, F. Fratianni, F. Nazzaro. Essential oils diversity of *Teucrium* species. *Teucrium species: Biology and applications* (179–210). Cham: Springer International Publishing (2020)
  36. F. Raei, N. Ashoori, F. Eftekhari, M. Yousefzadi, Chemical composition and antibacterial activity of *Teucrium polium* essential oil against urinary isolates of *Klebsiella pneumoniae*. *J. Essent. Oil Res.* **26**(1), 65–69 (2014)
  37. A. Ciocarlan, I. Dragalin, A. Aricu, L. Lupascu, N. Ciocarlan, K. Vergel, I. Zinicovscaia, Chemical profile, elemental composition, and antimicrobial activity of plants of the *Teucrium* (Lamiaceae) genus growing in Moldova. *Agronomy.* **12**(4), 772 (2022)
  38. Z. Timizar, K. Boutemak, A. Hadj Ziane-Zafour, N. Touzout, H. Tahraoui, B. Jaouadi, A. Amrane, Comprehensive analysis of phytochemical composition, antioxidant potential, and antibacterial activity of *T. polium*. *Separations.* **11**(4), 90 (2024)
  39. F. Khodaei, Mitochondrial effects of *Teucrium polium* extract in colorectal cancer cells. *Asian Pac. J. Cancer Prev.* **19**(1), 103–109 (2018)
  40. F. Hashem-Dabaghian, Anti-mutagenicity and apoptotic effects of *Teucrium polium* essential oil in HT-29 cells. *Jundishapur J. Nat. Pharm. Prod.* **15**(3), e79559 (2020)
  41. F. Guesmi, Terpenes from *Teucrium alopecurus* Essential Oil Trigger Apoptosis in Human Colon Cancer Cells. *Oncotarget.* **9**, 32305–32320 (2018)
  42. S. Garzoli, Natural essential oils as therapeutic tools in colorectal cancer. *Cancer Cell Int.* **22**, 477 (2020)
  43. M. Weston, S. Geng, R. Chandrawati, Food sensors: challenges and opportunities. *Adv. Mater. Technol.* **6**(5), 2001242 (2021)
  44. S. Yasar, H. Şen Arslan, K. Akgul, Increased reactive carboxyl and free alfa-amino groups from fish type I collagen peptides by Alcalase® hydrolysis exhibit higher antibacterial and antioxidant activities. *Int. J. Food Eng.* **20**(5), 315–330 (2024)
  45. S. Yasar, N.M. Nizamlioglu, H. Sen Arslan, M.O. Gucus, Infrared spectroscopic determination of acetamidiprid pesticide in apple. *Commun. Soil Sci. Plant Anal.* **54**(19), 2635–2644 (2023)

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.