Antioxidant and antimicrobial activities of fennel, ginger, oregano and thyme essential oils

Aysegul Mutlu-Ingok1,2 | Gizem Catalkaya1 | Esra Capanoglu1 | Funda Karbancioglu-Guler1

1 Department of Food Engineering, Faculty of Chemical and Metallurgical Engineering, Istanbul Technical University, Istanbul, Turkey
2 Department of Food Processing, Akcakoca Vocational School, Duzce University, Duzce, Turkey

Correspondence
Esra Capanoglu, Department of Food Engineering, Faculty of Chemical and Metallurgical Engineering, Istanbul Technical University, 34469 Maslak, Istanbul, Turkey
Email: capanoglu@itu.edu.tr

Abstract
In this study, the aim was to evaluate the antimicrobial and antioxidant activities of thyme (Thymus vulgaris), oregano (Origanum vulgare), ginger (Zingiber officinale) and fennel (Foeniculum vulgare) essential oils in addition to their chemical compositions. Based on the results of gas chromatography-mass spectrometry (GC–MS) analysis, major components were thymol and p-cymene in thyme, carvacrol, and p-cymene in oregano, α-zingiberene and ar-curcumene in ginger and (E)-anethole in fennel essential oils. Essential oils were investigated for their antimicrobial activities by agar well diffusion and broth microdilution methods against Campylobacter jejuni and Campylobacter coli. The inhibition zone diameters varied from 9.2 ± 0.7 to 28.7 ± 2.1 mm for C. jejuni and 14.7 ± 2.0 to 27.8 ± 2.8 mm for C. coli. While the minimum inhibitory concentrations (MICs) were lower for thyme and oregano EOs (5.65–43.20 μg/ml), the highest MIC value was obtained in fennel EO against C. jejuni (28530 μg/ml). Total phenolic contents and antioxidant activities of these essential oils were evaluated by using Folin Ciocalteu, 1,1-diphenyl-2-picrylhydrazyl (DPPH), Cupric Reducing Antioxidant Capacity (CUPRAC) and 2, 2-azinobis(3-ethylbenzo-thiazoline)-6-sulphonic acid (ABTS) methods. The total phenolic content of the essential oils ranged between 7.72 (ginger) to 193 (thyme) mg GAE/L. Antioxidant activities of thyme and oregano were found to be the highest according to the ABTS method, whereas thyme was found to be the highest by the CUPRAC method and ginger by the DPPH method.

KEYWORDS
antibacterial activity, antioxidant activity, Campylobacter spp., chemical composition, Foeniculum vulgare, Origanum vulgare, Thymus vulgaris, Zingiber officinale

1 | INTRODUCTION

Essential oils (EOs) are complex molecules obtained from different plant parts and contain different types of volatile molecules like terpenes and terpenoids, phenol-derived aromatic components and aliphatic components (Burt, 2004). EOs are used for pharmaceutical and flavoring purposes and are also becoming popular for inhibiting microbial growth and increasing the shelf-life of food products instead...
of synthetic preservatives because of consumers’ negative attitudes (Burt, 2004; Smith-Palmer et al., 1998). A well-known group of medicinal plants, Thymus species, have several biological and pharmacological properties, and their essential oils can be used as nutraceuticals and natural preservatives in foods (Mancini et al., 2015). Fennel (Foeniculum vulgare Mill., Fam. Umbelliferae) is also an important medicinal and aromatic plant with anti-inflammatory and antimicrobial effects (Mahfouz & Sharaf-Eldin, 2007). One of the oldest and the most widely used herbs, ginger, belongs to the Zingiberaceae family (Singh et al., 2008).

Oregano is another important aromatic plant that is commonly used for flavouring purposes and its essential oil has been used for centuries due to its medicinal properties (Quiroga et al., 2011). The antimicrobial activity of all these medicinal plants’ essential oils is mainly associated with their chemical composition and phytochemicals (Borguà et al., 2014). In this study, EOs from fennel, ginger, oregano and thyme have been selected considering their wide application due to their characteristic aroma and flavour, as well as their antimicrobial and antioxidant potential and medicinal properties.

Apart from having antimicrobial properties, many of the EOs have also been characterized as natural antioxidants (Ruberto & Baratta, 2000). Since they are natural antioxidants with the virtue of being non-toxic, research on EOs has been gaining more attention due to their potential use as preservatives, supplements, cosmeceuticals or nutraceuticals. This situation is incredibly worthwhile since most prevalent synthetic antioxidants are assumed to have potential adverse health effects. Many herbs and spices such as thyme, clove, cinnamon, rosemary, oregano and plant extracts such as tea contain components with antioxidant activities and are known to effectively hinder oxidation (Amorati et al., 2013; Brewer, 2011). For example, oregano EO, which is thymol and carvacrol-rich, has been shown to have a significant antioxidant effect on the process of lard oxidation (Kulisic et al., 2004). Another study by Tongnuanchan et al. (2013) revealed that root essential oils of ginger, turmeric and plai provided antioxidant activity when incorporated into fish skin gelatin.

There are several methods for determining the antimicrobial activities of EOs against different microorganisms. The most common methods are to measure the zone diameter (Friedman et al., 2002) and determine the minimum inhibition concentration (MIC). The type of microorganisms, test medium and concentration of EOs are important factors in implementing antimicrobial activity test methods (Zaïka, 1998). It is also essential to explain the particular mechanisms of antimicrobial action as well as their antimicrobial effects. EOs and their components have activity against a wide range of targets, especially the membrane and cytoplasm, by changing the cell morphology (Nazzaro et al., 2013). The mechanism of their antimicrobial activity was defined by their hydrophobicity resulting in increased cell permeability and leakage of cell constituents (Diao et al., 2014; Lambert et al., 2001).

Moreover, the antimicrobial activity of EOs has correlated with the diffusion ability of EOs (diffusion coefficient, zeta potential and droplet size of EOs) through the cell membrane of microorganisms (Mutlu-Ingok, Firtin et al., 2020b). Different factors affect the antimicrobial activity of EOs, such as microbial cultures, geographical origin, plant part from which EO was derived, extraction method and harvesting time (Mutlu-Ingok, Devecioglu et al., 2020a). Moreover, clinical and standard strains of microorganisms differed in terms of their sensitivities of EOs (Mutlu-Ingok et al., 2019).

Depending on the potential of EOs as antimicrobials and antioxidants, they can be alternatives to synthetic antioxidants/antimicrobials for conventionally produced foods. However, it is also vital to perform bacterial-based studies for their safe use. According to our literature survey, several research studies have investigated the antimicrobial activities of EOs; however, they have not been critically tested against Campylobacter spp. Campylobacter is one of the major foodborne pathogens, and raw poultry and its products are considered to be an important source. Although it was reported that Campylobacter spp. were present in 83% of the tested chickens in England (Jørgensen et al., 2002), reported data about Campylobacter infections in Turkey are comparatively restricted (Mutlu-Ingok & Karbancıoğlu-Güler, 2017). Depending on the increasing number of infections and resistance of microorganisms against antibiotics, essential oils were thought to be a good alternative to control these microorganisms by using their antimicrobial activities.

Another important aspect of this study is that EOs were investigated with respect to their both antimicrobial and antioxidant activities. This is important in terms of determining potential application areas of EOs by barring their biological activities. Also, considering the necessity of relating these biological activities to the chemical composition adds value to this work. In summary, this study aimed to investigate the antimicrobial and antioxidant activities of thyme, oregano, ginger and fennel EOs against Campylobacter jejuni and Campylobacter coli using different methods.

## 2 MATERIALS AND METHODS

### 2.1 Bacterial strains

C. jejuni (ATCC 33560) and C. coli (NCTC 12525) isolates were used in this study. The bacteria were kept in a medium containing 20% glycerol at -80°C. Bacterial strains were obtained from Refik Saydam National Type Culture Collection (RSDKK), Sıhhiye, Ankara.

### 2.2 Essential oils

Food-grade form of thyme (0.864 g/ml), oregano (0.94 g/ml), ginger (0.877 g/ml) and fennel (0.951 g/ml) EOs were obtained from International Flavors & Fragrances (IFF) Co., (Gebze, Kocaeli, Turkey). EOs were sterilized by filtration with 0.22 μm filters (Minisart® Syringe Filter, Sartorius Stedim Biotech GmbH, Germany). Dilutions were prepared in 10% Dimethyl sulfoxide (DMSO, Merck, Darmstadt, Germany). All samples were kept in the dark environment and 4°C.

### 2.3 Gas chromatography and gas chromatography-mass spectrometry

Gas chromatography (GC) analysis was performed using an Agilent 7890B GC system with a flame ionization detector (FID). The
chromatographic separations were achieved by the Agilent HP-Innowax column (60 m x 0.25 mm Ø, with 0.25 μm film thickness). The flow rate of helium as the carrier gas was set as 0.7 ml/min. GC oven temperature was kept at 60°C for 10 min and increased to 220°C at a rate of 4°C/min and then kept constant at 220°C for 10 min. Finally, the temperature was programmed to increase to 240°C at a rate of 1°C/min. The split ratio was 40:1, and the temperatures of injector and flame ionization detectors were set at 250°C. The relative percentage of essential oil compounds were calculated by using FID chromatograms.

GC-mass spectrometry (GC/MS) analysis was performed using an Agilent 7890B GC coupled with a 5977B MSD (Agilent, Palo Alto, CA; SEM A. S., Istanbul, Turkey). Analytical conditions and the column were the same as both GC/MS and GC/FID. The mass range was recorded from m/z 35 to 450. The temperature of the injector was set to 250°C. Mass spectra were taken at 70 eV. Relative retention indices (RRI) were calculated by using alkanes. The identification of EO constituents was achieved using Wiley 9-Nist 11 mass spectral database and standard Alkan series (C7–C40). Moreover, results were supported by comparing the retention indices with the literature.

### 2.4 Agar well diffusion assay

Inhibition zone diameters were determined using a previously described method of Deans and Ritchie (1987), with slight modifications. Bacterial cultures were grown in Mueller–Hinton Broth (MHB, Merck, Darmstadt, Germany). After incubation at 42°C for 48 h in microaerophilic conditions generated using Anaerocult® C (Merck, Darmstadt, Germany), bacterial suspension concentrations were adjusted to approximately 10^8 CFU/ml. 100 μl of bacterial suspensions were added to Campylobacter blood-free agar base (Modified CCDA, Merck, Darmstadt, Germany). Three wells with a 6 mm diameter are punched by a sterile corkbore and 2.5–20 μl of EOs were introduced into each well. After inoculation, plates were incubated at 42°C (thyme: 0.1–5 g/L; oregano: 0.1–5 g/L; ginger: 0.01–0.1 g/L; fennel: 0.5 mg/ml; oregano 0.5 mg/ml; ginger 5 mg/ml; fennel 10 mg/ml) was added to the test tubes followed by the addition of 2.5 ml 0.2 N Folin–Ciocalteu’s reagent and 2 ml sodium carbonate (7.5% w/v). After vortexing, incubation of the tubes was performed at 50°C for 5 min. Absorbance was measured at 760 nm and the calculated results were expressed as Gallic Acid Equivalents (GAE) in milligrams per liter of EO. All samples were analyzed in triplicate.

### 2.5 Broth microdilution assay

The broth microdilution method was used to determine minimum inhibitory concentrations (MICs) (Wiegand et al., 2008). Serial doubling dilutions of EOs were prepared with 10% DMSO. After sub-culturing and adjusting the bacterial suspension concentrations to approximately 10^8 CFU/ml. Wells that added 95 μl of MHB and 100 μl serial EO dilutions were inoculated with 5 μl of microbial inoculum. Wells with inoculum but without EO and wells with EO but without inoculum were defined as the positive and negative control, respectively. The incubation of the microplates was done at 42°C for 24 h under microaerophilic conditions. Experiments were run in triplicate and MIC values were determined spectrophotometrically by measuring optical density with a microplate reader (Synergy HT, BioTek Instruments Inc., Winooski, VT, USA). For establishing the minimum bactericidal concentration (MBC), after MIC test, broths from the wells (included MHB, isolates, and EOs) were inoculated on modified CCDA and microaerophilic incubation was performed. While MIC was the lowest bacteriostatic concentration, MBC was the lowest bactericidal concentration.

### 2.6 Total phenolic content

The total phenolic content of the EOs was analyzed using the Folin–Ciocalteu assay (Viuda-Martos et al., 2010). Briefly, 300 μl of an ethanolic solution (containing 1% DMSO) of essential oils (EOs; thyme 0.1 mg/ml; oregano 0.5 mg/ml; ginger 5 mg/ml; fennel 10 mg/ml) was added to the test tubes followed by the addition of 0.2 ml of 10% Folin–Ciocalteu’s reagent and 2 ml sodium carbonate (7.5% w/v). After vortexing, incubation of the tubes was performed at 50°C for 5 min. Absorbance was measured at 760 nm and the calculated results were expressed as Gallic Acid Equivalents (GAE) in milligrams per liter of EO. All samples were analyzed in triplicate.

### 2.7 Determination of total antioxidant activity

Determination of total antioxidant activities of the EOs were done by three methods: DPPH (1,1-diphenyl-2-picrylhydrazyl), CUPRAC (cupric reducing antioxidant capacity) and ABTS (2,2-azino-bis-3-ethylbenzthiazoline-6-sulphonic acid). All analyses were run in triplicate and ethanol was used as a blank. DPPH method was performed according to Kulisic et al. (2005a). 50 μl of ethanolic solution (containing 10% DMSO) of essential oils with varying concentrations (thyme: 0.1–5 g/L; oregano: 0.1–5 g/L; ginger: 0.01–0.1 g/L; fennel: 10–50 mg/ml) was introduced in a tube. After adding 1 ml of 0.004% ethanolic solution of DPPH, the absorbance of the control sample was measured immediately and the rest of the samples were incubated for 1 h in the dark. The IC₅₀ value, expressed as the sample amount required for decreasing the absorbance of DPPH by 50%, was calculated by plotting % of inhibition against the sample concentration. The percentage inhibition of the DPPH radical was calculated by using the following equation:

\[
\% \text{ inhibition} = \left( \frac{A_{C(0)} - A_{EO(t)}}{A_{C(0)}} \right) \times 100
\]

where \( A_{C(0)} \) is the absorbance of the control at \( t = 0 \) min and \( A_{EO(t)} \) is the absorbance of the essential oil at the end of the incubation time.

Copper reducing antioxidant capacity (CUPRAC) was determined according to Apak et al. (2004). 100 μl of ethanolic solution (containing 10% DMSO) of essential oils was placed in a tube and mixed with 1 ml of 10 mM CuCl₂, 7.5 mM neocuproine and 1 M NH₄Ac (pH 7). Immediately, 1 ml of distilled water was added to the mixture to make the
final volume of 4.1 ml. After 30 min of incubation at room temperature, absorbance was read at 450 nm against a reagent blank. The results were expressed as mg Trolox equivalent antioxidant capacity (TEAC)/L EO.

ABTS analysis was carried out according to Miller and Rice-Evans (1997) with slight modifications. ABTS radical was prepared by mixing ABTS and potassium persulfate solutions and keeping at room temperature in the dark overnight. ABTS radical stock solution was diluted in 50 mM potassium phosphate buffer (pH 8.0) until its absorbance reaches 0.90 ± 0.2 at 734 nm and the pH of the final mixture was adjusted to 7.4. Then, 100 μl of ethanolic solution (containing 10% DMSO) of essential oil with varying concentrations (0.01–0.1 g/L for thyme and oregano; ginger and fennel were not analysed since they produced a white turbidity when they came into contact with the solutions) was mixed with 1 ml of ABTS and the absorbance was measured at 734 nm, 30 seconds or 1 min after initial mixing. The IC50 values of the samples were determined as defined above in the DPPH method by using Equation 1.

### 2.8 Statistical analysis

All experiments were conducted in triplicate and the obtained data were reported as mean ± standard deviation. Statistical analysis was carried out using SPSS software (version 20.0, SPSS, Chicago, IL, USA). Mean values were compared using one-way analysis of variance (ANOVA) followed by Tukey post hoc test, and p < 0.05 was considered as significant.

### 3 RESULTS AND DISCUSSION

#### 3.1 Chemical composition of essential oils

The chemical composition of the EOs, which were identified based on GC and GC-MS, is shown in Table 1. They involved a complex mixture of monoterpenoid hydrocarbons, oxygenated monoterpenes, and sesquiterpenoid hydrocarbons. Major components of EOs were thymol and p-cymene in thyme, carvacrol, and p-cymene in oregano, α-zingiberene, and ar-curcumene in ginger and (E)-anethole in fennel EOs. Identified components and their concentrations in this study were comparable to the results reported in the literature. α-Pinene, the monoterpenoid hydrocarbon, was existent with relatively low concentrations in tested EOs. Varga et al. (2015) reported that in Thymus vulgaris and Thymus pulegioides, thymol was the main component with percentages of 32.20% and 27.40%, respectively. Borugá et al. (2014) found p-cymene (8.41%), γ-terpinene (30.90%) and thymol (47.59%) as major components in Thymus vulgaris EO. In accordance with these studies, thymol was the main component (46.4%) in thyme EO, and p-cymene (23.3%), Linalool (6.3%) and carvacrol (4.6%) were also detected in significant amounts in our study. Some researchers have reported that antimicrobial activities of Thymus EOs were mainly associated with the presence of phenolic compounds (thymol and carvacrol) (Rota et al., 2008), which can also be supported with the findings of the current work. According to the literature, while cymene does not show antibacterial activity individually, because of the lack of hydroxyl group, its synergistic antibacterial activity has been reported with carvacrol and thymol (Ultee et al., 2002). Oregano EO was found to consist of a mixture of several compounds dominated by two, namely carvacrol (69.9%) and p-cymene (17.0%). The composition of oregano EO has been characterized with carvacrol and thymol as the main compounds (Figiel et al., 2010), but the proportions vary widely depending on the plant’s geographical origin, different parts of the plants, mode of extraction and harvesting season (Burt, 2004). Recent results showed that antimicrobial activity of oregano EO is characterized by the phenol constituents, thymol and carvacrol and their two precursor monoterpenoid hydrocarbons, γ-terpinene and p-cymene.

The high content of (E)-anethole (81.4%) in fennel EO observed in this study is closed to the values stated by Viuda-Martos et al. (2011) and Diao et al. (2014). On the other hand, α-fenchone (4.7%) was the second primary compound detected. Limonene, α-pinene, methyl chavicol, and α-phellandrene were also detected as minor components in the corresponding EO.

It has been mentioned that the specific aroma of ginger is predominantly related to the content of zingiberene (Kamalirostaa et al., 2013). Similar to other studies, α-zingiberene (31.6%), belonging to the sesquiterpene hydrocarbons, was the main compound of ginger EO in our study (Kamalirostaa et al., 2013; Saisidharan & Menon, 2010). Zingiberene (31.6%) was followed by ar-curcumene (19.30%) and β-bisabolene (9.2%). While minor variations were detected, the tested essential oils’ composition was generally in agreement with the values reported by different authors.

#### 3.2 Antimicrobial activities of essential oils

The antimicrobial activities of thyme, oregano, ginger and fennel EOs against Campylobacter spp. examined in the current study and their potential was evaluated by the diameter of inhibition zones and minimum inhibition concentrations. Minimum bactericidal concentrations were also detected. The antibacterial activities of essential oils measured by diffusion and dilution methods are shown in Tables 2 and 3.

Some studies refer to the high antimicrobial effect of EOs and plant extracts against Campylobacter spp. (Aslim & Yucel, 1998; Friedman et al., 2002). However, there are also controversial results reported, which indicates the resistance of Campylobacter spp. against EOs and plant extracts (Klančnik et al., 2010, Smith-Palmer et al., 1998). It has been suggested that for plant EOs, inhibition zone diameter not only depends on the uniform diffusion of the antimicrobial agent into the test medium but also the release of vapor from the oil on bacteria (Friedman et al., 2002).

In the current study, C. jejuni and C. coli showed varying degrees of sensitivity to all tested EOs depending on the EO type. Among tested EOs, larger inhibition zones against both C. jejuni and C. coli were obtained using oregano and thyme EOs. Similar to our results, Smith-Palmer et al. (1998) reported the most effective EO as thyme against
## TABLE 1 Chemical composition of thyme, oregano, ginger and fennel essential oils

| No | Compounds | RI<sup>a</sup> | RI<sup>b</sup> | Peak area<sup>a</sup> (%) |
|----|-----------|----------------|---------------|--------------------------|
|    |           |                | Thyme | Oregano | Fennel | Ginger |
| 1  | α-Pinene  | 1032<sup>1</sup> | 1034  | 1.8     | 3.1    | 1.3    |
| 2  | Camphene  | 1076<sup>2</sup> | 1079  | -       | -      | 3.7    |
| 3  | Myrcene   | 1174<sup>1</sup> | 1173  | 1.4     | -      | -      |
| 4  | α-Phellandrene | 1176<sup>1</sup> | 1177  | -       | -      | 1.3    |
| 5  | Limonene  | 1203<sup>1</sup> | 1210  | 1.1     | -      | 3.2    |
| 6  | 1,8 cineole | 1213<sup>1</sup> | 1220  | -       | -      | -      |
| 7  | β-Phellandrene | 1118<sup>1</sup> | 1222  | -       | -      | 2.4    |
| 8  | γ-Terpinene | 1255<sup>1</sup> | 1260  | 3.7     | 2.3    | -      |
| 9  | p-Cymene  | 1280<sup>1</sup> | 1287  | 23.3    | 17.0   | -      |
| 10 | α-Fenchone | 1406<sup>4</sup> | 1418  | -       | -      | 4.7    |
| 11 | Linalool  | 1553<sup>1</sup> | 1552  | 6.3     | 2.1    | -      |
| 12 | β-Elemene | 1600<sup>3</sup> | 1610  | -       | -      | 1.2    |
| 13 | Terpinen-4-ol | 1611<sup>1</sup> | 1619  | 1.4     | -      | -      |
| 14 | β-Caryophyllene | 1612<sup>2</sup> | 1626  | 1.5     | -      | -      |
| 15 | Methyl chavicol | 1687<sup>4</sup> | 1693  | -       | -      | 2.9    |
| 16 | Borneol   | 1719<sup>1</sup> | 1721  | 1.1     | -      | -      |
| 17 | α-Zingiberene | 1720<sup>5</sup> | 1747  | -       | -      | 31.6   |
| 18 | β-Bisabolene | 1741<sup>1</sup> | 1752  | -       | -      | 9.2    |
| 19 | γ-Muurolene | 1704<sup>2</sup> | 1754  | -       | -      | 2.3    |
| 20 | (E,E)-α-Farnesene | 1758<sup>1</sup> | 1764  | -       | -      | 6.7    |
| 21 | β-Sesquiphellandrene | 1771<sup>5</sup> | 1795  | -       | -      | 3.3    |
| 22 | ar-Curcumene | 1773<sup>5</sup> | 1798  | -       | -      | 19.3   |
| 23 | (E)-Anethole | 1845<sup>4</sup> | 1865  | -       | -      | 81.4   |
| 24 | Thymol    | 2198<sup>1</sup> | 2201  | 46.4    | 3.6    | -      |
| 25 | Carvacrol | 2239<sup>1</sup> | 2239  | 4.6     | 69.9   | -      |

<sup>a</sup>Identification was based on the comparison of mass spectra and co-injection with standard Alkan series (C<sub>7</sub>–C<sub>40</sub>).  
<sup>b</sup>Retention indices obtained from literature: ([Babushok et al., 2011]<sup>5</sup>; [Kosar et al., 2005]<sup>4</sup>, [Sevindik et al., 2016]<sup>2</sup>, [Tabanca et al., 2004]<sup>1</sup>, [Wannes, Mhamdi, & Marzouk, 2009]<sup>3</sup>).  
<sup>c</sup>Retention indices relative to standard Alkan series (C<sub>7</sub>–C<sub>40</sub>).  
<sup>d</sup>Peak areas were obtained by GC-FID.  
<sup>e</sup>Compounds lower than 1% or not identified. The technical variation of samples did not exceed 10%.

## TABLE 2 The diameter of the inhibition zone and MIC values of essential oils against C. jejuni

| Essential oils | MIC<sup>1</sup> (µg/ml) | MBC<sup>2</sup> (µg/ml) | Diameter of inhibition zone (mm) |
|----------------|-----------------------------|---------------------------|---------------------------------|
|                | 2.5µl | 5µl | 10µl | 20µl | 2.5µl | 5µl | 10µl | 20µl |
| Thyme          | 21.60 | 21.60 | 13.3 ± 1.7 | 15.5 ± 1.0 | 20.4 ± 1.2 | 28.7 ± 2.1 |
| Oregano        | 5.65  | 5.65  | 14.4 ± 1.2 | 19.8 ± 1.9 | 24.5 ± 4.6 | 28.5 ± 4.4 |
| Ginger         | 6577.50 | 6577.50 | NT<sup>3</sup> | NA<sup>4</sup> | 9.2 ± 0.7 | 17.2 ± 2.6 |
| Fennel         | 28,530.00 | 28,530.00 | NT | NT | NA | 17.9 ± 3.7 |
| Streptomycin<sup>5</sup> | NT | NT | NT | 21.3 ± 2.1 | 24.7 ± 1.5 | 30.0 ± 1.3 |

Values represent average values ± standard deviations of triplicate experiments;  
<sup>1</sup>Minimum inhibition concentrations;  
<sup>2</sup>Minimum bactericidal concentrations;  
<sup>3</sup>Not tested;  
<sup>4</sup>No activity;  
<sup>5</sup>Standard antibiotic.
five pathogen microorganisms including C. jejuni but with a smaller inhibition zone diameter (10.4 mm) compared with our results (28.7 ± 2.1 mm). These differences might be due to the composition, concentration and/or the type of EOs (Aslim & Yucel, 1998). The extraction method, as well as the differences in the strain, were also effective on the antimicrobial activity of EOs. For the orange-based fractions, the diameter of the inhibition zones has been reported to be between 11 and 44 mm against 14 different strains of C. jejuni as published by Nannapaneni et al. (2009). In another study for C. jejuni (ATCC 33560), MIC values ranged from 0.08 to 0.31 μg/ml depending on the rosemary extract formulations (Piskernik et al., 2011).

The antimicrobial activities of thyme and oregano EOs were compared favorably with streptomycin (Tables 2 and 3). On the other hand, other EOs had lower antimicrobial effects than streptomycin. Similarly, among thyme, fennel and ginger EOs, Smith-Palmer et al. (1998) have determined thyme as the most inhibitory against C. jejuni. Contrary to this, ginger and fennel EOs were observed to have high bacteriostatic and bactericidal concentrations.

Determination of minimum inhibition and bactericidal concentrations are more sensitive than the agar well diffusion method (Smith-Palmer et al., 1998). The microdilution method is also economical because of less waste of time and resources and provides accurate results. According to Klančnik et al. (2010), MIC values obtained by the microdilution method were the same or lower compared to other dilution methods. It means that the microdilution method results are more susceptible than other antimicrobial activity testing methods.

Minimum inhibition and bactericidal concentrations of thyme, oregano, ginger and fennel EOs obtained by broth microdilution method were also examined to express the antimicrobial activity. As seen in Tables 2 and 3, lower inhibition and bacteriostatic concentrations were required for oregano EO. Thus, C. jejuni and C. coli were the most sensitive to oregano among all tested EOs. Aslim and Yucel (1998) also reported significant antimicrobial activity of endemic origanum essential oil against Campylobacter spp. MIC values were in the range of 12.5–700 and 7.8–800 μg/ml for C. jejuni and C. coli, respectively. As a result of the current study, the MIC value for both C. jejuni and C. coli was 5.65 μg/ml. On the other hand, inhibition zone diameters were supported by MIC values in our study.

Studies about the antibacterial activities of fennel EO are restricted. These studies have mainly focused on E. coli O157:H7, Listeria monocytogenes, Salmonella Typhimurium, Staphylococcus aureus, Staphylococcus albus, Bacillus subtilis, Pseudomonas aeruginosa and Shigella dysenteriae (Dadalioglu & Evrendilek, 2004, Diao et al., 2014). In this study, fennel EO had the lowest inhibition zones and the highest MIC values. Friedman et al. (2002) reported that fennel seed oil was the most ineffective oil compared to cardamon, cumin seed, dill weed, ginger, oregano and thyme EOs. In our study, fennel and ginger EOs showed the lowest antimicrobial effect against C. jejuni and C. coli by both agar diffusion and microdilution assay methods. In contrast with the current study, Friedman et al. (2002) reported ginger EO as effective against C. jejuni.

Numerous studies examined the minimum inhibition and bacteriostatic concentrations of EOs on some pathogen microorganisms, but studies related to Campylobacter spp. are still limited. Moreover, most of the studies are about the antimicrobial effects of EOs but their action mechanism is still unclear (Lambert et al., 2001).

### 3.3 Total phenolic content and antioxidant activities of essential oils

The total phenolic contents of thyme, oregano, fennel and ginger EOs, as presented in Figure 1, are reported as mg gallic acid equivalent/L essential oil. The total phenolic content (TPC) of thyme EO was found to be significantly higher, which corresponds to 193 mg GAE/L while oregano EO had a value of 163 mg GAE/L. On the other hand, fennel was found to have less TPC (17.7 mg GAE/L) than thyme and oregano, while ginger showed the lowest amount among the four EOs (7.72 mg GAE/L). In a similar study by Viuda-Martos et al. (2010), the TPC of EOs from thyme, oregano, rosemary, clove, and sage was investigated. Their results also showed that thyme and oregano EOs were the richest sources of phenolic compounds within the studied EOs. Another research by Gan et al. (2016) indicated that ginger EO had the lowest...
The total phenolic content (TPC) of EOs is an important indicator of their antioxidant properties. Ozcan et al. (2009) reported the TPC of EO obtained from thyme, oregano, ginger, and fennel essential oils (*Gallic acid equivalent). Different letters indicate statistically significant differences between EOs (p < 0.05).

Several studies have shown that polyphenols from different origins exhibit antioxidant properties (Cai et al., 2004; Zheng & Wang, 2001), and the content of phenolic compounds might be correlated with their antioxidant activities. In this study, three different assays were used for determining the antioxidant capacities of EOs since a single method may not be sufficient to fully understand the antioxidant activity of a substance as each method has advantages and disadvantages. DPPH and ABTS methods are based on the reaction of a potential antioxidant with a colored radical (i.e., DPPH+ or ABTS+•), whereas the CUPRAC method is based on the reaction of an antioxidant compound with Cu²⁺ ions having oxidizing properties (Apak et al., 2016). These methods are generally considered as useful in screening the antioxidant content of natural extracts or matrices since they are easy, simple and reasonably costly methods (Alam et al., 2013; Amorati & Valgimigli, 2015). On the other hand, biological methods testing antioxidant activity have several advantages such as better reflecting the real situation in biological systems, but they may be expensive, time-consuming and may not be sufficient to fully understand the antioxidant activity of a substance as each method has advantages and disadvantages.

DPPH and ABTS methods are based on the reaction of a potential antioxidant with a colored radical (i.e., DPPH• or ABTS••), whereas the CUPRAC method is based on the reaction of an antioxidant compound with Cu²⁺ ions having oxidizing properties (Apak et al., 2016). These methods are generally considered as useful in screening the antioxidant content of natural extracts or matrices since they are easy, simple and reasonably costly methods (Alam et al., 2013; Amorati & Valgimigli, 2015). On the other hand, biological methods testing antioxidant activity have several advantages such as better reflecting the real situation in biological systems, but they may be expensive, time-consuming and may not be sufficient to fully understand the antioxidant activity of a substance as each method has advantages and disadvantages.

The total antioxidant capacity (TAC) of the EOs with the DPPH assay was demonstrated in Figure 2, where the results are given as the per cent inhibition. The highest antioxidant activity was observed in ginger EO with an IC50 value of 1.66 g/L. It was followed by thyme and oregano EOs showing a similar inhibition concentration as 4 and 4.34 g/L, respectively. However, no statistically significant difference was observed between these three EOs (p > 0.05). Fennel EO was found to have the weakest antioxidant activity with an IC50 value of 270 g/L (p < 0.05). The results obtained for thyme and oregano were similar to the results reported by Bozin et al. (2006), indicating that thyme and oregano showed higher antioxidant activities (with similar IC50 values of 0.19 and 0.17 μg/mL, respectively) than basil EO or the synthetic antioxidant, BHT. Research on the ginger EO showed that this EO exhibited 100% inhibition of DPPH between the concentrations of 5–20 μL/mL (in this study, the concentration range of ginger oil was 0.011–0.114 μL/mL since higher concentrations caused turbidity in the reaction mixture, thus affected the accuracy) (Amorati et al., 2013). In contrast to our findings, IC50 values determined by DPPH assay of EOs from three fennel cultivars have shown to vary from 0.35 to 15.33 g/L (Shahat et al., 2011), which have relatively higher antioxidant activities than the fennel EO tested in this study.

Figure 3 reflects the antioxidant activity of thyme, oregano, ginger, and fennel EOs in terms of Trolox equivalent antioxidant activity per liter sample as assessed by the CUPRAC method. Within the four EOs, thyme EO displayed significantly higher antioxidant activity (634 mg TEAC/L) than other EOs (p < 0.05). The antioxidant capacities of oregano, ginger and fennel were found as 122, 84.0 and 8.5 mg TEAC/L, respectively. Similar to the DPPH results, fennel EO exhibited remarkably lower antioxidant activity than the other studied EOs. In a recent study, antioxidant properties of eight EOs from thyme, clove buds, cinnamon, lemon balm, cedar, lemon, mandarin and rosemary have been determined to be within the range of 0.25 to 4.60 mg TEAC/g. Among them, clove and thyme EOs were found to be the most antioxidative oils (4.60 and 4.30 mg TEAC/g, respectively) (Olszowy & Dawidowicz, 2016). Furthermore, Deng et al. (2016) investigated the antioxidant properties of thymol, which is the most abundant component of thyme EO, and expressed the antioxidant activity measured by the CUPRAC method as 0.95 mg TEAC/g. However, it should be considered that this value belongs only to one of the components of thyme, not the whole sample. On the other side, the antioxidant activities of ginger and fennel EOs could not be compared with the literature since the data on the antioxidant activity of essential oils determined by the CUPRAC method are very scarce.

Total antioxidant capacities of the EOs with the ABTS assay are demonstrated in Figure 4 and the results are given as the per cent inhibition. According to the results, there was no significant difference between thyme and oregano essential oils (p > 0.05) and they displayed the same IC50 value detected as 0.08 g/L. These results are in line with the results obtained from the DPPH assay indicating that the same concentrations of essential oils are required to inhibit the 50% of DPPH or ABTS radicals. However, no reliable data could be obtained for ginger and fennel EOs since they interfered with the reaction solutions and became cloudy. On the other hand, the difference between the magnitude of the values obtained by DPPH and ABTS methods may be attributed to the distinctness of the assays. For example, the background color formed due to the matrix exhibits utmost adverse effects on the precision of color-fading reactions such as DPPH and ABTS (Apak et al., 2016). It has been also reported in the literature that IC50 values obtained with different methods may vary significantly. For example, in a study by Bendaoud et al. (2010), the IC50 value determined by DPPH assay of Schinus molle L. EO was found to be almost 14-fold higher than the IC50 value determined by the ABTS assay. In another study, the IC50 value of pimento EO was app. two-fold higher with DPPH method compared to ABTS method (Padmakumari et al., 2011).

In a study performed by Spagnoletti et al. (2016), the IC50 value of EO from thyme was determined as 0.58 mg/L, which has markedly lower antioxidant activity than the sample studied in this work.
In contrast with this study, the IC\textsubscript{50} value of thyme oil, measured by the ABTS assay, was reported to be higher than oregano oil (17 and 32 g/L, respectively).

The antioxidant potential of an EO can be more or less predicted by considering its composition. In general, a good antioxidant property is expected if the EO contains high amounts of phenolic compounds (Amorati et al., 2013). However, different fractions of the EOs may act differently in the prevention of oxidation. For example, Kulisic et al. (2005b) examined the effect of different fractions of EOs on lard oxidation inhibition. They revealed that hydrocarbon fraction of several EOs had no effect on the inhibition of oxidation or had a pro-oxidant effect while oxygenated fraction (dominantly containing thymol and carvacrol) of these EOs showed a better effect on the extension of induction time of the lard oxidation.

On the other hand, in some EOs, these two fractions showed a synergistic effect, which means the highest antioxidant activity was obtained when the whole EO is used. In another study, the antioxidant properties of thymol, carvacrol, 6-gingerol, hydroxytyrosol and zingerone were tested in phospholipid liposome systems and a decrease in the per-oxidation of phospholipid liposomes was observed when thymol, carvacrol, 6-gingerol and hydroxytyrosol were used. However, zingerone showed only a weak inhibitory effect on the oxidation of phospholipid liposome system (Aeschbach et al., 1994). Considering this information, better antioxidant properties and total phenolic content of thyme
and oregano tested in this study may be linked with their thymol and carvacrol content. Ruberto and Baratta (2000) reported that monoterpenes hydrocarbons (especially terpinolene, α- and γ-terpinene), which are among the tested 99 pure EO components, showed a significant effect on the prevention of oxidation on two lipid model systems. According to Table 1, the predominant monoterpenes hydrocarbons, p-cymene, and γ-terpinene are only detected in thyme and oregano EOs. Thus, their antioxidant activity may also be linked to their p-cymene and γ-terpinene contents. 

As a result, although the antioxidant properties of the EOs in this study are mostly in accordance with the literature, their levels and efficacy greatly vary, which may be related to the diversity of the EOs based on plant’s geographical origin, different parts of plants, extraction mode and harvesting season (Burt, 2004). In addition to their antioxidant activity, their antimicrobial activities were also crucial for controlling corresponding microorganisms (Mutlu-Ingok & Karbancioglu-Guler, 2017).

4 | CONCLUSIONS

One possible method for preventing or retarding the growth of pathogenic microorganisms and deterioration in agricultural products and foods could be using natural antimicrobials alone or together with other preservation techniques. Although all tested essential oils in the current study exhibited antimicrobial activity against C. jejuni and C. coli, oregano EO exerted the most potent inhibitory effect against Campylobacter spp. On the other hand, thyme and oregano EOs were found to be the most potent antioxidants and rich sources of phenolic compounds among the other EOs. It seems apparent that the antimicrobial activity was primarily associated with the presence of remarkable levels of carvacrol and thymol. The findings of this study showed the potential use of oregano EO as well as other tested EOs for food applications, but high concentrations of EOs may cause organoleptic changes in foods which should be considered in further studies.

CONFLICT OF INTEREST

The authors declare that they have no competing interest.

ACKNOWLEDGMENTS

The authors wish to thank Anadolu University, Medicinal Plants, Drugs and Scientific Research Center (AUBIBAM), Eskisehir, Turkey for GC and GC/MS analyses. This research was supported by Istanbul Technical University, Scientific Research Projects (Project no. 38819).

ORCID

Aysegul Mutlu-Ingok https://orcid.org/0000-0001-9571-0053
Gizem Catalkaya https://orcid.org/0000-0003-4749-8734
Ersan Capanoglu https://orcid.org/0000-0003-0335-9433
Funda Karbancioglu-Guler https://orcid.org/0000-0001-6576-0084

REFERENCES

Aeschbach, R., Lüöiger, J., Scott, B. C., Murcia, A., Butler, J., Halliwell, B., & Aruoma, O. I. (1994). Antioxidant actions of thymol, carvacrol, 6-gingerol, zingerone and hydroxytyrosol. *Food and Chemical Toxicology*, 32(1), 31–36.
Alam, M. N., Bristi, N. J., & Rafiquzzaman, M. (2013). Review on in vivo and in vitro methods evaluation of antioxidant activity. *Saudi Pharmaceutical Journal*, 21(2), 143–152.
Amorati, R., Foti, M. C., & Valgimigli, L. (2013). Antioxidant activity of essential oils. *Journal of Agricultural and Food Chemistry*, 61(46), 10835–10847.
Amorati, R., & Valgimigli, L. (2015). Advantages and limitations of common testing methods for antioxidants. *Free Radical Research*, 49(5), 633–649.
Apak, R., Guclu, K., Ozurek, M., & Karademir, S. E. (2004). Novel total antioxidant capacity index for dietary polyphenols and vitamins C and E using their cupric ion reducing capability in the presence of neocuproine.
CUPRAC method. Journal of Agricultural and Food Chemistry, 52(26), 7970–7981.

Apak, R., Ozyurek, M., Guclu, K., & Capanoglu, E. (2016). Antioxidant activity/capacity measurement. 1. Classification, physicochemical principles, mechanisms, and electron transfer (et)-based assays. Journal of Agricultural and Food Chemistry, 64(5), 997–1027.

Aslim, B., & Yucel, N. (1998). In vitro antimicrobial activity of essential oil from endemic Origanum minutiflorum on ciprofloxacin-resistant Campylobacter spp. Food Chemistry, 107(2), 602–606.

Babushok, V. I., Linstrom, P. L., & Zhenekh, I. G. (2011). Retention indices for frequently reported compounds of plant essential oils. Journal of Physical and Chemical Reference Data, 40(4), 043101.

Bendaud, H., Romdhane, M., Souchard, J. P., Cazaux, S., & Bouajila, J. (2010). Chemical composition and anticancer and antioxidant activities of Schinus molle L. and Schinus terebinthifolius Raddi berries essential oils. Journal of Food Science, 75(4), C466–C472.

Borugá, O., Jianu, C., Mişcă, C., Goleţ, I., Gruia, A. T., & Horhat, F. G. (2014). Thymus vulgaris essential oil: Chemical composition and antimicrobial activity. Journal of Medicine and Life, 7(3), 56–60.

Bozin, B., Mimica-Dukic, N., Simin, N., & Anackov, G. (2006). Characterization of the volatile composition of essential oils of some lamiaceae spices and the antimicrobial and antioxidant activities of the entire oils. Journal of Agricultural and Food Chemistry, 54(5), 1822–1828.

Brewer, M. S. (2011). Natural Antioxidants: Sources, Compounds, Mechanisms of Action, and Potential Applications. Comprehensive Reviews in Food Science and Food Safety, 10(4), 221–247.

Burt, S. (2004). Essential oils: Their antibacterial properties and potential applications in foods—a review. International Journal of Food Microbiology, 94, 223–253.

Cai, Y., Luo, Q., Sun, M., & Corke, H. (2004). Antioxidant activity and phenolic compounds of 112 traditional Chinese medicinal plants associated with anticancer. Life Sciences, 74(17), 2157–2184.

Dadalioğlu, I., & Evrendilek, G. A. (2004). Chemical compositions and antibacterial effects of essential oils of Turkish oregano (Origanum minutiflorum), bay laurel (Laurus nobilis), Spanish lavender (Lavandula stoechas L.), and fennel (Foeniculum vulgare) on common foodborne pathogens. Journal of Agricultural and Food Chemistry, 52(26), 8255–8260.

Deans, S. G., & Ritchie, G. (1987). Antibacterial properties of plant essential oils. International Journal of Food Microbiology, 5(2), 165–180.

Deng, L. L., Taxipalati, M., Que, F., & Zhang, H. (2016). Physical characterization and antioxidant activity of thymol solubilized Teween 80 micelles. Scientific Reports, 2016, 6. ARTN 3816010.1038/srep38160.

Diao, W. R., H., Q.-P., Zhang, H., & Xu, J.-G. (2014). Chemical composition, antibacterial activity and mechanism of action of essential oil from seeds of fennel (Foeniculum vulgare Mill.). Food Control, 35(1), 109–116.

Figiel, A., Szumny, A., Gutiérrez-Ortíz, A., & Carbonell-Barrachina, Á. A. (2010). Composition of oregano essential oil (Origanum vulgare) as affected by drying method. Journal of Food Engineering, 98(2), 240–247.

Frankel, E. N., & Finley, J. W. (2008). How to standardize the multiplicity of methods to evaluate natural antimicrobials. Journal of Agricultural and Food Chemistry, 56(13), 4901–4908.

Friedman, M., Henika, P. R., & Mandrell, R. E. (2002). Bactericidal activities of plant essential oils and some of their isolated constituents against Campylobacter jejuni, Escherichia coli, Listeria monocytogenes, and Salmonella enterica. Journal Food Protection, 65(10), 1545–1560.

Gan, Z., Liang, Z., Chen, X., Wen, X., Wang, Y., Li, M., & Ni, Y. (2016). Separation and preparation of 6-gingerol from molecular distillation residue of Yunnan ginger rhizomes by high-speed counter-current chromatography and the antioxidant activity of ginger oils in vitro. Journal of Chromatography B, 1011, 99–107.

Jørgensen, F., Bailey, R., Williams, S., Henderson, P., Wareing, D. R., Bolton, F. J., Forest, J. A., Ward, L., & Humphrey, T. J. (2002). Prevalence and numbers of Salmonella and Campylobacter spp. on raw, whole chickens in relation to sampling methods. International Journal of Food Microbiology, 76(1-2), 151–164.
Piskernik, S., Klšečnik, A., Riedel, C. T., Brandsted, L., & Možina, S. S. (2011). Reduction of Campylobacter jejuni by natural antimicrobials in chicken meat-related conditions. Food Control, 22(5), 718–724.

Quiroga, P. R., Riveros, C. G., Zygodlo, J. A., Grosso, N. R., & Nepote, V. (2011). Antioxidant activity of essential oil of oregano species from Argentina in relation to their chemical composition. International Journal of Food Science & Technology, 46(12), 2648–2655.

Rota, M. C., Herrera, A., Martinez, R. M., Sotomayor, J. A., & Jordán, M. J. (2008). Antimicrobial activity and chemical composition of Thymus vulgaris, Thymbry zygis and Thymbry hyemalis essential oils. Food Control, 19(7), 681–687.

Ruberto, G., & Baratta, M. T. (2000). Antioxidant activity of selected essential oil components in two lipid model systems. Food Chemistry, 69(2), 167–174.

Sasidharan, I., & Menon, A. N. (2010). Comparative chemical composition and antimicrobial activity fresh and dry ginger oils (Zingiber officinalis Roscoe). International Journal of Current Pharmaceutical Research, 2(4), 4–7.

Sevindik, H. G., Özek, T., Yerdelen, K. Ö., Önál, M., Özberk, H., Güvenalp, Z., & Demírezer, L. Ö. (2016). Chemical composition, antioxidant capacity, acetyl- and butyrylcholinesterase inhibitory activities of the essential oil of thyme haussknchtii velen. Records of Natural Products, 10(4), 503–507.

Shahat, A. A., Ibrahim, A. Y., Hendawy, S. F., Omer, E. A., Hamouda, F. M., Abdel-Rahman, F. H., & Saleh, M. A. (2011). Chemical composition, antimicrobial and antioxidant activities of essential oils of organically cultivated fennel cultivars. Molecules, 16(2), 1366–1377.

Singh, G., Kapoor, I. P., Singh, P., de Heluani, C. S., de Lampasona, M. P., & Catalán, C. A. (2008). Chemistry, antioxidant and antimicrobial investigations on essential oil and oleoresins of Zingiber officinalis. Food and Chemical Toxicology, 46(10), 3295–3302.

Smith-Palmer, A., Stewart, J., & Fyfe, L. (1998). Antimicrobial properties of plant essential oils and essences against five important foodborne pathogens. Letters in Applied Microbiology, 26(2), 118–122.

Spagnoletti, A., Guerrini, A., Tacchini, M., Vinciguerra, V., Leone, C., Maresca, I., Simonetti, G., Sacchetti, G. & Angiolella, L. (2016). Chemical composition and bio-efficacy of essential oils from Italian aromatic plants: Mentha suaveolens, Coriophymus capitatus, Origanum hirtum and Rosmarinus officinalis. Natural Product Communications, 11(10), 1517–1520.

Tabanca, N., Özek, T., Baser, K. H. C., & Tümen, G. (2004). Comparison of the essential oils of origanum majorana L. and Origanum x majoricum Cambess. Journal of Essential Oil Research, 16(3), 248–252.

Tongnuechan, P., Benjakul, S., & Prodpran, T. (2013). Physico-chemical properties, morphology and antioxidant activity of film from fish skin gelatin incorporated with root essential oils. Journal of Food Engineering, 117(3), 350–360.

Ultee, A., Bennik, M. H. J., & Moezelaar, R. (2002). The phenolic hydroxyl group of carvacrol is essential for action against the foodborne pathogen Bacillus cereus. Applied and Environmental Microbiology, 68(4), 1561–1568.

Varga, E., Bardocz, A., Belák, Á., Maráz, A., Boros, B., Felinger, A., Böszörmenyi, A. & Horváth, G. (2015). Antimicrobial activity and chemical composition of thyme essential oils and the polyphenolic content of different Thymus extracts. Farmacia, 6(3), 357–361.

Viuda-Martos, M., Mohamady, M. A., Fernández-López, J., Abd ElRazik, K. A., Omer, E. A., Pérez-Alvarez, J. A., & Sendra, E. (2011). In vitro antioxidant and antibacterial activities of essentials oils obtained from Egyptian aromatic plants. Food Control, 22(11), 1715–1722.

Wannes, W. A., Mhamdi, B., & Marzouk, B. (2009). Variations in essential oil and fatty acid composition during Myrtus communis var. italicus fruit maturation. Food Chemistry, 112(3), 621–626.

Wiegaard, I., Hilpert, K., & Hancock, R. E. W. (2008). Agar and broth dilution methods to determine the minimal inhibitory concentration (MIC) of antimicrobial substances. Nature Protocols, 3(2), 163–175.

Zaika, L. L. (1998). Spices and herbs: Their antimicrobial activity and its determination. Journal of Food Safety, 25(1), 13–19.

Zheng, W., & Wang, S. Y. (2001). Antioxidant activity and phenolic compounds in selected herbs. Journal of Agricultural and Food Chemistry, 49(11), 5165–5170.

How to cite this article: Mutlu-Ingok, A., Catalkaya, G., Capanoglu, E., & Karbanciglu-Guler, F. (2021). Antioxidant and antimicrobial activities of fennel, ginger, oregano and thyme essential oils. Food Frontiers., 1–11. https://doi.org/10.1002/fft2.77