

Investigating the effect of gamma-ray interaction on the stability and physicochemical properties of turmeric and ginger using Monte Carlo simulation

Beyza Vahapoglu^{a,1}, Ozge Kilicoglu^{b,c,*}, Nur Cebi^d, Mehmet Turan Ayseli^{e,f}, Umit Kara^g, Osman Sagdic^d, Esra Capanoglu^a

^a Department of Food Engineering, Faculty of Chemical and Metallurgical Engineering, Istanbul Technical University, 34469 Maslak, Istanbul, Turkey

^b Vocational School of Health Services, Marmara University, Kartal, Istanbul, Turkey

^c Radiation Laboratory, University of Notre Dame, Notre Dame, IN, 46556-5670, USA

^d Department of Food Engineering, Faculty of Chemical and Metallurgical Engineering, Yıldız Technical University, 34210 Esenler, Istanbul, Turkey

^e Faculty of Hamidiye Pharmacy, University of Health Sciences Turkey, 34668, Uskiidar, Istanbul, Turkey

^f Genetris Danışmanlık, 33340, Mezitli, Mersin, Turkey

^g Süleyman Demirel University, Vocational School of Health Services, Medical Imaging Department, Isparta, Turkey

ARTICLE INFO

Keywords:

Gamma-irradiation
Turmeric
Ginger
Antioxidant activity
Monte Carlo simulation

ABSTRACT

Turmeric and ginger are among the most widely used medicinal plants due to their health benefits and bio-activities, which include antiviral and antioxidant properties. However, these plants are usually irradiated to increase their shelf life and quality. Using a Monte Carlo simulation, this study investigates the structural changes in the active ingredients of ginger and turmeric after irradiation. The Linear Attenuation Coefficient (LAC) and Mass Attenuation Coefficient (MAC) calculations are interrelated with the properties of materials in terms of low and high radiation absorption. According to the results, curcumin showed better absorption attributes compared to 6-gingerol. The results also indicated an increase in the total antioxidant activity and b value (yellowness) of turmeric after treatment with 5 kGy irradiation. On the other hand, positive correlations were also found between MAC and ABTS values. It can be concluded that irradiation up to 5 kGy dosages could be beneficial for turmeric as it both prevents microbial contamination and increases its antioxidant activity. However, the results indicated that the effect of irradiation on the antioxidant activity varies depending on the nature of the product, thus further studies are required to better understand the effect of irradiation on the bioactive components of food materials.

1. Introduction

Over the last few decades, consumers' purchasing habits have clearly shifted towards functional foods, nutraceuticals, medicinal herbs, and spices. Consumers prefer healthier foods to enhance their immune system, especially following the new viral pneumonia outbreak in 2019. Ginger (*Zingiber officinale Roscoe*) and turmeric (*Curcuma Longa*) are two important therapeutic herbs that are frequently consumed not only for their flavor and scent but also for their health benefits (Ayseli et al., 2020).

Ginger is a medicinal plant that has been widely consumed for its anti-emetic, anti-obesity (Ayseli and Ayseli, 2016), anti-influenza

(Rasool et al., 2017), and antiviral (Ferrara, 2019) activities, as well as for anti-tuberculosis treatment (ATT) (Rasool et al., 2017) and migraines (Bhandari et al., 1998). Several studies have also been published about the structural phenols of ginger, which show similar effects to acetylsalicylic acid (CAS No: 50-78-2). The main pharmacological active constituents of ginger, mainly 6-gingerol and shogaols, have been shown to be effective on prostaglandins, prostaglandin E2 (PGE2), and prostaglandin F2 alpha (PGF2 alpha), as well as thromboxane, leading to their potential use as a platelet aggregation inhibitor. Previous studies in animals have reported that the use of the ethanolic extract of the ginger root causes a noteworthy decrease in lipid peroxidation due to its effect on antioxidant enzymes such as superoxide dismutase (SOD) (Bhandari

* Corresponding author. Vocational School of Health Services, Marmara University, Kartal, Istanbul, Turkey.

E-mail address: okilicog@nd.edu (O. Kilicoglu).

¹ These authors contributed equally to this work.

Table 1
Elemental compositions, and density of selected active ingredients^b of samples.

Element	[6]-Gingerol ^a	Curcumin ^a
CAS No ^b	23513-14-6	458-37-7
% Carbon (C)	69.36	68.47
% Hydrogen (H)	8.90	5.47
% Oxygen (O)	21.74	26.06
Density (g/cm ³)	1.1±0.1	1.3±0.1

^a 6-gingerol is active ingredient of ginger; curcumin is active ingredient of turmeric.

^b CAS No: Chemical Abstracts Service Number.

et al., 1998).

Turmeric (*Curcuma Longa*) is a widely used plant in food supplements in different forms, including liposomal capsules, chewable tablets, and lozenges, in addition to its use in cooking as a spice. Curcumin, the main active ingredient in turmeric, has been indicated to show anti-inflammatory, antiviral, and antioxidant activities (Ayseli et al., 2020). Curcumin has been reported to have a similar activity to that of acetylsalicylic acid and antiviral drugs. This active substance is claimed to be an antiviral drug candidate for patients with lung tissue damage resulting from the coronavirus infection.

The main problem with spices and medicinal herbs are microbial contamination from soil, handling practices (Almeida et al., 2018), and storage environment (Variyar et al., 1997). Microbial contamination risk in plants including turmeric is quite high, although turmeric powder is produced from boiled roots and dried rhizomes (Almeida et al., 2018). On the other hand, the use of ethylene oxide (ETO), methyl bromide (MB), and ethylene dibromide (EDB) as chemical methods to minimize microbial contamination has been either prohibited or restricted because of their environmental contamination risk (Matin, 2001). Considering these facts, food irradiation was indicated to be an effective method to improve the shelf life and quality of foods, food supplements, and pharmaceuticals (Magdy et al., 2020).

Despite substantial research on the effects of gamma irradiation on food (Magdy et al., 2020), no study has been undertaken to analyze the structural changes in active components of ginger and turmeric after irradiation. Taking advantage of this gap in the existing literature, the goal of this study is to investigate radiation interactions of active ingredients of ginger and turmeric (6-gingerol and curcumin) after 5 KGy of gamma irradiation. By using a Monte Carlo simulation, this study then determines the antioxidant activity and physicochemical properties of the samples.

2. Materials and methods

2.1. Materials

Non-irradiated, medicinal, and aromatic plant samples, ginger and turmeric, were purchased from a local producer in Turkey (Köryusuf Ltd. Sti, Mersin, Turkey). The samples were packaged in polyethylene bags of 1 kg each and stored at ambient temperature until further processing. Table 1 lists the elemental compositions of 6-gingerol and curcumin. The majority of the elements were composed of C, H, N, and O with density values ranging from 1.1±0.1 to 1.3±0.1 g/cm³.

2.2. Food irradiation

Samples of 200 g medicinal plants (MP) were packed in polyethylene bags for irradiation using a Cobalt 60 gamma irradiator (Red Harwell 3042 PMMA, Oxfordshire, United Kingdom) at Gamma Pak Sterilizasyon San.ve Tic. A.S (Turkey). The dose applied to the sample was 5 kGy (minimum 4.2-maximum 5.2 kGy) and at a dose of 1 kGy/h at room temperature (23 °C). One sample of each non-irradiated turmeric (NIT) and non-irradiated ginger (NIG) (dose 0) was used as a control for comparisons. The irradiated turmeric (IT) and irradiated ginger (IG)

were stored in sealed plastic bags at 4 °C until testing. The irradiation treatments were performed at Gamma Pak Sterilizasyon San.ve Tic. A.S (Turkey).

2.3. Characterization of irradiated and non-irradiated turmeric and ginger

2.3.1. Antioxidant activity determination

2.3.1.1. CUPRAC (Cupric reducing antioxidant capacity) method. CUPRAC method was performed as described by Apak et al. (2004). 1 ml of CuCl₂·2H₂O (10 mM), 1 ml of Neocuproine (7.5 mM), and 1 ml of NH₄CH₃COO (pH 7) were mixed. Then, 0.1 µL of the extract and 1 ml of distilled water were added to the mixture, respectively. The absorbances of the mixtures were recorded at 450 nm after 30 min. The antioxidant activity of samples was expressed as mg Trolox equivalent per g sample.

2.3.1.2. ABTS (2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt) method. ABTS method was performed as described by Miller and Rice-Evans (1997). 200 ml of ABTS (0.11%) was mixed with 2 ml of potassium persulfate (1.9%) and stored overnight in the dark for radicalization. The solution was diluted with potassium phosphate buffer (pH 8, 0.05 M) until its absorbance reached 0.9±0.2. Then, 1 ml of the final solution was added to 100 µL of the extract and, the mixture was vortexed. The antioxidant activity of samples was reported as mg Trolox equivalent per g sample.

2.3.1.3. Determination of total phenolic content (TPC). The methanol extract of each sample was obtained before spectrophotometric analysis. 75% methanol was used as a solvent and ultrasonic-assisted extraction was applied. Total phenolic content was determined as described by Singleton and Rossi (1965) with slight modifications. 0.1 ml of the extract and 0.75 ml Folin Ciocalteu reagent (1:10 diluted) were mixed. After 5 min, 0.6 ml of Na₂CO₃ (7.5%) was added to the mixture. The absorbance of mixtures was recorded at 765 nm after 90 min incubation in the dark. The total phenolic compound was measured as mg gallic acid equivalent (GAE) per g sample.

2.3.2. Raman measurements

Dried turmeric and ginger samples to be used in Raman measurement were ground with a coffee grinder (Fakir Hausgeräte, Stuttgart, Germany). Ground plants were placed in clear Raman vials (5 cc).

Spectral measurements of IT, NIT, IG, and NIG samples were performed with a portable-Raman spectrometer Progeny (Rigaku Raman Technologies, Wilmington, MA, USA). The yttrium aluminum garnet (YAG) laser was oscillated near-infrared at 1064 nm for Raman measurements at the spectral range of 2000–200 cm⁻¹. The exposure time and laser power were set to 0.851s and 0.25 W, respectively. After repeating each sample analysis 10 times, the average spectrum was calculated for chemometrics (Camp & Cicerone, 2015).

2.3.3. Morphology analysis using scanning electron microscopy (SEM)

The morphological structure of the products was analyzed using the SEM device. First, the dry powder portions were dispersed and glued to 25 mm diameter plates, and then attached to the sample slots. The samples were analyzed by sputter coating with a gold layer 5 nm thick (about 180 s) and analyzed by an electron microscope (Phenom, USA) (Kara et al., 2020).

2.3.4. Color properties

Color properties (L, a, and b values) of the samples were measured with a CR-400 handheld chroma meter (Minolta, Tokyo, Japan).

Table 2
Chemical composition and antioxidant activity of turmeric and ginger samples.

Analysis	NIT	IT	NIG	IG	Sig. *
Total phenolics (mg/g GAE) ^x	21.44±1.46 ^a	26.35 ±1.59 ^a	13.13±0.47 ^b	8.77 ±0.20 ^b	ns
ABTS (mg/g TE) ^y	48.63±3.07 ^a	60.39 ±0.63 ^b	33.53±0.63 ^c	20.35 ±2.81 ^d	*
CUPRAC (mg/g TE) ^y	53.45±1.45 ^a	49.15 ±1.62 ^a	42.93±2.53 ^b	25.68 ±1.31 ^c	*
L (Brightness)	49.15±0.73 ^a	53.56 ±0.57 ^a	87.21±0.23 ^b	84.82 ±1.39 ^b	ns
a (Redness)	18.37±0.69 ^a	19.84 ±0.40 ^a	-2.46 ±0.06 ^b	-0.91 ±0.12 ^b	ns
b (Yellowness)	43.33±1.07 ^a	53.96 ±0.61 ^b	24.85±0.37 ^c	21.70 ±0.30 ^c	*

x GAE: Gallic acid equivalent; ^yTE: Trolox equivalent; *: Significant, significance at which means differ as shown by analysis of variance (p < 0.05); ns: not significant. NIT: Non-irradiated turmeric; IT: Irradiated turmeric; NIG: Non-irradiated ginger; IG: Irradiated.

2.3.5. Monte Carlo simulation

2.3.5.1. Theoretical basis. The factor of gamma-ray attenuation of the samples was examined for food irradiation using Monte Carlo Simulation. Lambert's Beer Law, from which LAC (μ) is also derived, can be found in the following equation:

$$I / I_0 = \exp[-(\mu / \rho)x] \quad (1)$$

$$\mu = \ln\left(\frac{I_0}{I}\right) / x$$

The transmitted and incident photon intensities are represented by "I₀" and "I," respectively, while "x" is the mass thickness of the gamma-ray attenuation material. MathWorks developed MATLAB, which is a software application for scientific and engineering calculations (MathworksInc., 2009). Matrix computation, algorithm implementation, simulation, charting of functions and data, signal processing, and image processing are all possible with MATLAB (Wilson et al., 2003). MCNP-4C, FOTELP-2K6, and other computer algorithms are used around the world to model photon transport in three-dimensional materials (Perutka, 2010).

Using the MATLAB tool, the MAC was computed analytically. The results were compared to those received from the widely used WinX-COM software program for validation purposes. The mixing rule is used to determine the partial and total MAC for all elements, mixtures, and compounds at the standard, as well as specified energies. The chemical compositions of the researched selected active components of samples are shown in Table 1. For theoretical calculations of irradiation qualities, the MAC and LAC are both critical attenuation parameters. At the theoretical level, the LAC (μ) refers to the quality of the attenuator.

Table 3

Pearson's correlation coefficients of total phenolics, antioxidant activities, color parameters, Mass Attenuation coefficient (MAC) and Half Value Layer (HVL).

Analysis	TPC	CUPRAC	ABTS	LAC	MAC	HVL	L	a	b
TPC	1								
CUPRAC	0.878*	1							
ABTS	0.930**	0.949**	1						
LAC	0.036	-0.042	0.178	1					
MAC	-0.106	-0.174	0.038*	0.986	1				
HVL	-0.136	-0.507	-0.286	-0.992	-0.962**	1			
L (Brightness)	-0.966**	-0.950**	-0.991	-0.123	0.023	0.228	1		
a (Redness)	0.957**	0.940**	0.951**	0.166	0.020	-0.273	-0.998	1	
b (Yellowness)	0.957**	0.951**	0.996	0.133	-0.012	-0.240	-0.999	0.999	1

*, **: Significant, significance at which means differ as shown by analysis of variance (p < 0.05) or (p < 0.01); ns: not significant.

Average values are expressed as mean±S.D. of three replicate determinations.

TPC (Total phenolic compounds); ABTS (2,2' azinobis (3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt) method; CUPRAC (Cupric reducing antioxidant capacity) method; LAC (Linear Attenuation coefficient); MAC (Mass Attenuation coefficient); HVL (Half Value Layer).

The density of the attenuator sample ratio assures μ , and the MAC (μ_p , cm²/g) represents how an incident energy beam penetrates the material. The MAC characterizes the absorbing material and is derived from the ratio of LAC divided by absorber density. The μ_p values for the manufactured selected samples were calculated using MATLAB and the WinXCOM application. For this, the following equation was employed.

$$\mu_m = \sum_i w_i \left(\frac{\mu}{\rho}\right)_i \quad (2)$$

The average distance traveled by a photon before colliding with something is called the mean free path (MFP). As a result, the MFP tells us how much the intensity of incident photons decreases by a factor of 1/e.

$$MFP = \frac{1}{\mu} \quad (3)$$

There is one important parameter related to the material thickness: the half value of the layer (HVL). The HVL stands for a material thickness that reduces radiation by half. The following equation was used to calculate HVL:

$$HVL = \left(\frac{\ln 2}{\mu}\right) \quad (4)$$

2.3.6. Statistical analysis

The analysis of the model established in this study was tested by One-way analysis of variance (ANOVA) and Tukey's test (p < 0.05) using Statistical Analysis Software (SPSS version 27. Inc.). Correlations between data were calculated using Pearson's correlation coefficient (r).

3. Results and discussion

3.1. Total phenolic content (TPC)

Total phenolic contents of irradiated and non-irradiated turmeric and ginger are reported in Table 2. There was no significant difference in the total phenolic content of IT, NIT, IG, and NIG samples. Obtained results of ginger were found to be correlated with those in the literature. Almeida et al. (2018) reported that they did not observe any significant difference in the phenolic content of the irradiated ginger samples despite increasing irradiation doses (0, 5, 10, 15, and 20 kGy). However, different studies showed different results for turmeric. In a study, 10 kGy doses of irradiation caused a decrease in the total phenolic content of turmeric while higher doses (15, 20 kGy) did not create any significant difference (Almeida et al., 2018). In another study, 10 kGy radiation did not affect the phenolic content of turmeric (Chatterjee et al., 2009). The discrepancy between different findings could be attributed to factors other than radiation exposure, such as sample composition and structure, phenolic profile, and temperature (Khattak et al., 2008).

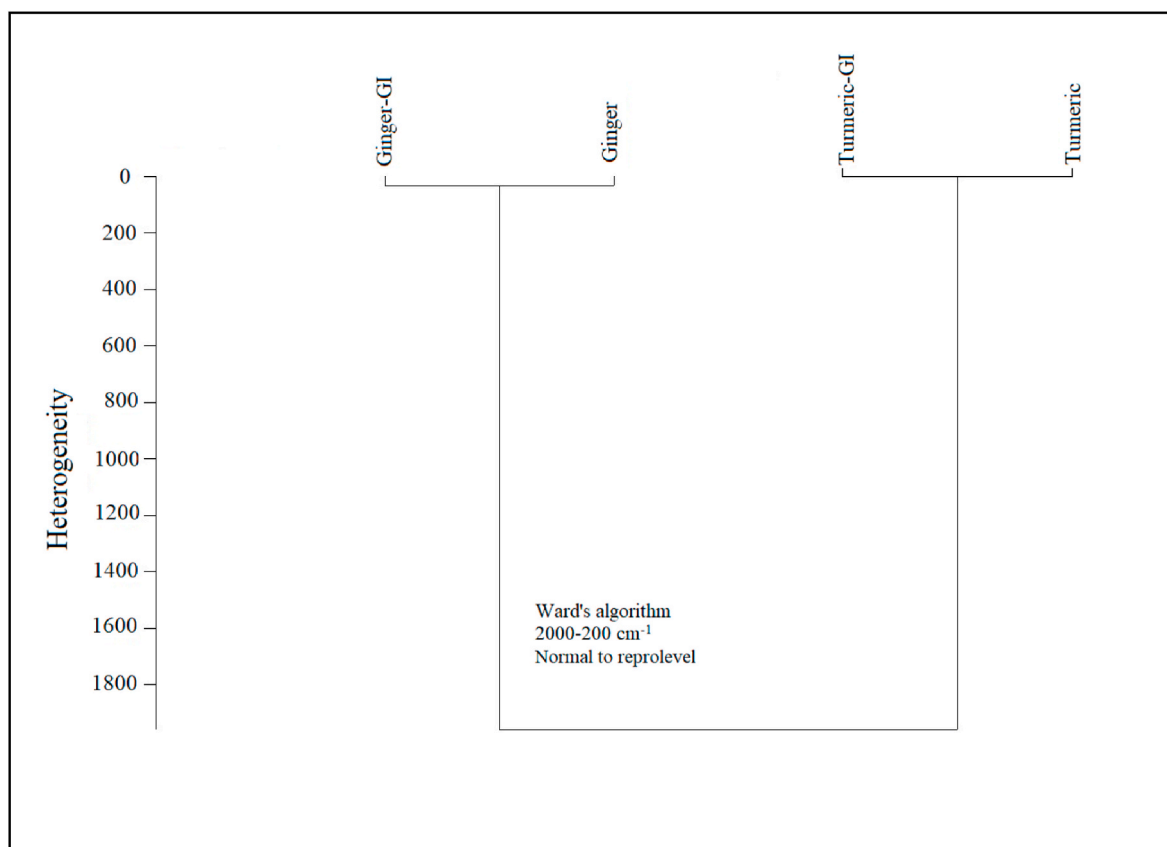


Fig. 1a. HCA (hierarchical cluster analysis) dendrogram of control and gamma-irradiated medicinal and aromatic plants on the basis of their Raman spectra (Turmeric: Non-irradiated turmeric; Turmeric-GI: Irradiated turmeric; Ginger: Non-irradiated ginger; Ginger-GI: gamma-irradiated ginger sample).

3.2. Total antioxidant activity

It is known that the irradiation process may cause the formation of free radicals and radiation-induced degradation (Alothman et al., 2009). Therefore, a decrease in antioxidant activity is generally expected. However, there are also some studies observing an increase in antioxidant activity after the irradiation process (Kim et al., 2008). This study indicated that the effect of irradiation on the antioxidant activities varied depending on the product. In the ABTS method, while there was a 19% increase in the antioxidant activity of turmeric, there was a 39% decrease in the antioxidant capacity of irradiated ginger (Table 2). The positive correlation between ABTS and TPC, and TPC and CUPRAC were observed with correlation coefficients (r) of 0.930 and 0.878, respectively (Table 3). That means the high antioxidant activity occurs due to high phenolic compounds in the selected samples.

In the CUPRAC method, similar to the ABTS method, there was a 40% decrease in the antioxidant activity of the IG sample. However, no significant differences in the antioxidant activity of IT and NIT were observed. Different results were presented in the literature for ginger. For example, Almeida et al. (2018) did not find a significant difference between 10 kGy IT and NIT samples with the DPPH test. However, they found a significant decrease in the antioxidant activity index. In another study, Byun et al. (1999) showed that 10 kGy gamma radiation had no effect on the antioxidant activity index of 16 herbal species including turmeric. Obtaining different results in our study may be an indication of the differences arising from the method applied. Other studies also found similar results indicating differences among different assays for black pepper (Suhaj et al., 2006), Brazilian mushroom (*Agaricus blazei*) (Huang & Mau, 2006), carrot, and kale juices (Song et al., 2006).

3.3. Color properties

Color change, especially in spices, is very important in terms of consumers' acceptance. Color values of samples for this study are presented in Table 2, where the most significant change was observed in b values (yellowness) for all samples. According to the results, the b value of turmeric samples ranged from 43.33 ± 1.07 to 53.96 ± 0.61 . However, after irradiation at 5 kGy, the b value showed a significant increase, which can be associated with the breakdown of glycosidic and peptide linkages triggered by the irradiation process (Sirisoontarak & Noomhorm, 2007). The color change may also be due to curcumin hydroxylations in IT, which cause a brighter yellow color (Madhusankha et al., 2018). There was a significant difference in b values as well as ABTS values ($p < 0.05$). Our research findings are quite consistent with those reported by Madhusankha et al. (2018), where the b value of standard turmeric was found to be 54.77 ± 0.39 . In our study, no significant difference was detected in other samples, except the increase in the b^* value of turmeric (Table 2).

However, after irradiation at 5 kGy, the b value of NIG and IG samples showed a significant decrease ($p < 0.05$), from 24.85 ± 0.37 and 21.70 ± 0.30 , respectively. A significant color change was not observed in the products such as red pepper (Lee et al., 2004) and a slight change was observed for whole grain rice (Shao et al., 2013) and pine nut kernels (Gölge & Ova, 2008) after irradiation applications.

3.4. Raman measurements

Raman spectroscopy provides an intrinsic fingerprint of evaluated materials based on their Raman spectra (Camp & Cicerone, 2015). Raman spectroscopy provides unique fingerprint properties of investigated compounds which are composed of lipids, proteins,

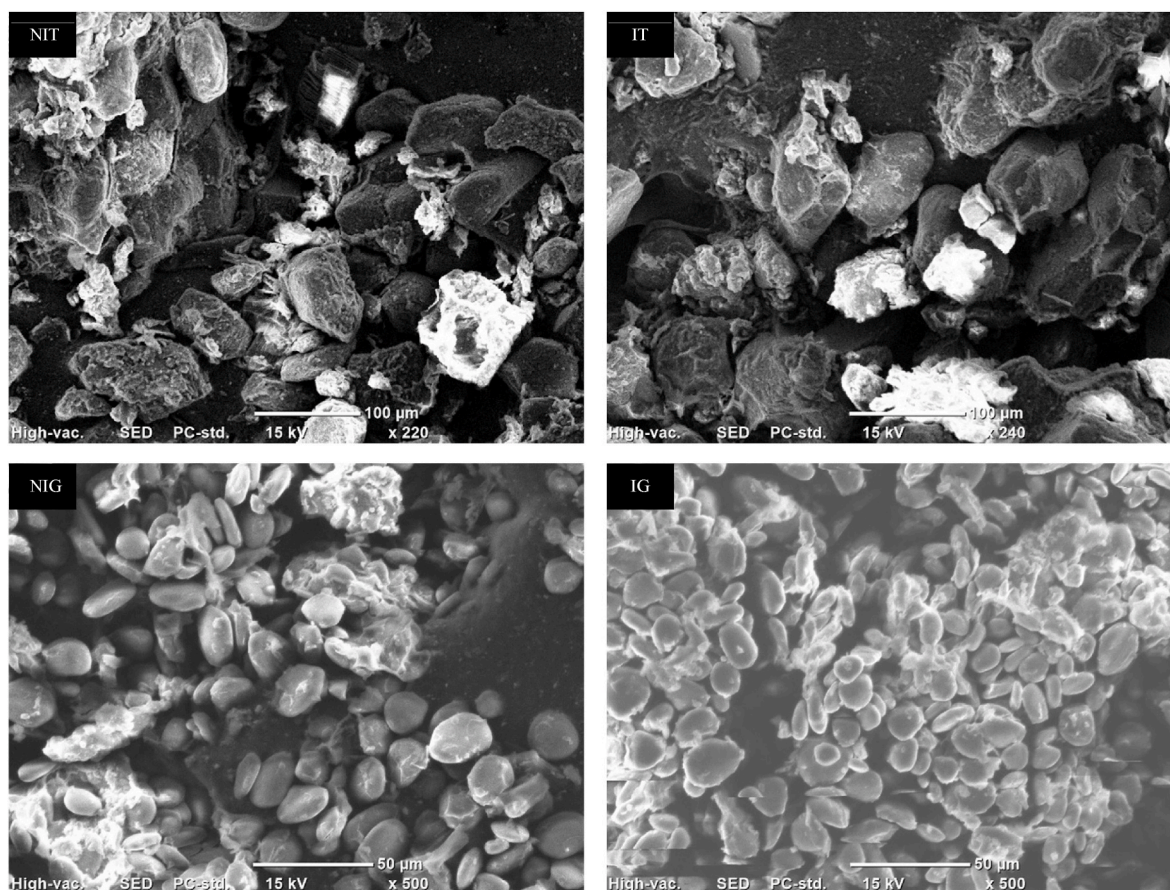


Fig. 1b. Scanning electron micrographs of turmeric and ginger (NIT: non-irradiated turmeric, IT: irradiated turmeric, NIG: non-irradiated ginger, IG: irradiated ginger).

carbohydrates, and minor compounds such as dyes, pigments, and flavorings (Ellis et al., 2012).

Control and gamma-irradiated samples of turmeric and ginger plants were evaluated using hierarchical cluster analysis based on their Raman data. Hierarchical cluster analysis was carried out by using OPUS Version 7.2 (Bruker, Germany) software. The spectral range of 2000–200 cm^{-1} was selected for hierarchical cluster analysis using the first-derivative Raman spectra of evaluated samples. The dendrogram was built using Ward's algorithm through normal to reprolevel algorithm. Known as the minimum variance method, Ward's method joins at each stage of the cluster pair whose merger minimizes the increase in the total within-group error sum of squares. In other words, Ward's method minimizes the increase in the total within-cluster sum of the squared

error (Taylan et al., 2021). HCA is a widely used unsupervised pattern recognition technique that is employed to extract intrinsic information from experimental data. Hierarchical clustering techniques are based on the creation of branched structures, called dendrograms that are qualitative in nature and permit visualization of clusters and correlations between samples (Gad et al., 2013).

In this study, hierarchical cluster analysis (HCA) was applied to monitor the gamma-irradiation of selected medicinal and aromatic plants. The hierarchical cluster was effectively used in previous authenticity and food chemistry issues of various compounds such as essential oils and food additives (Gad et al., 2013; Taylan et al., 2021; Tulukcu et al., 2019). The HCA dendrogram of control and gamma-irradiated selected plants is presented in Fig. 1a. As can be seen

Table 4

The mass attenuation coefficients (cm^2/g) values derived from MATLAB and WinXCOM for selected samples and their relative deviations.

[6]-Gingerol ^a				Curcumin ^b			
MeV	Matlab	WinXcom	% Dev	MeV	Matlab	WinXcom	% Dev
0.02	0.526477	0.528	0.00213	0.02	0.547154	0.548	0.00209
0.06	0.192454	0.192	0.001843	0.06	0.187962	0.188	0.001928
0.08	0.176475	0.176	0.004409	0.08	0.171694	0.171	0.004644
0.122	0.159462	0.156	0.023506	0.122	0.151269	0.151	0.00046
0.356	0.109568	0.109	0.007985	0.356	0.105374	0.105	0.00025
0.511	0.094128	0.094	0.001996	0.511	0.091213	0.091	0.001904
0.662	0.084877	0.084	0.011165	0.662	0.081522	0.081	0.002243
1.173	0.064633	0.064	0.010681	1.173	0.062006	0.062	0.000585
1.25	0.062087	0.062	0.003016	1.25	0.060163	0.060	0.003052
1.33	0.060227	0.060	0.004447	1.33	0.058361	0.058	0.004489

^a [6]-Gingerol is active compound of ginger.

^b Curcumin is active compound of turmeric.

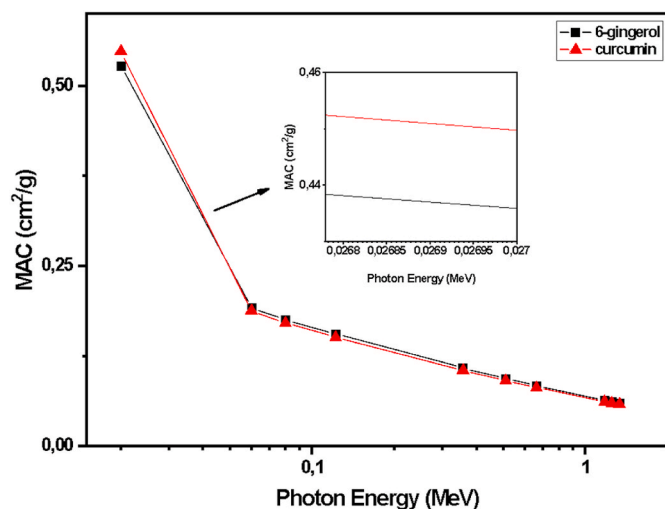


Fig. 2a. Variations of mass attenuation coefficients (MAC) with photon energy for 6-gingerol and curcumin.

from the figure, control and gamma-irradiated samples were clustered as different branches of the dendrogram based on the obtained Raman data. These results support the idea of using Raman spectroscopy and chemometrics to discriminate gamma-irradiated medicinal and aromatic plants from non-irradiated ones. The results of this study confirm previous ones. It has been shown that vibrational spectroscopy (FTIR and Raman) is successfully applied to monitor spectral changes of investigated compounds related to the applied gamma radiation since vibrational spectroscopy techniques such as Raman spectroscopy present unique chemical-fingerprint properties of materials (Oliveira et al., 2019; Teixeira et al., 2018; Yasmin et al., 2019).

3.4.1. Morphology analysis using scanning electron microscopy

The scanning electron microscopy of the native and 5 kGy irradiated turmeric and ginger is presented in Fig. 1b. Both ginger and turmeric samples had irregular shapes and uneven surfaces as seen in previous studies in the literature (Valizadeh Kiamahalleh et al., 2016). In our study, no difference in the visible change in the morphology of the samples was observed after 5 kGy irradiation. This result is in agreement with that of Mukisa et al. (2012) where similar results were observed in irradiated sorghum starch

3.5. Attenuation coefficients

The MAC for the studied samples is computed with WinXCOM and MATLAB programs between 0.02 and 1.33 MeV. Table 4 summarizes the outcomes of WinXCOM and MATLAB simulations. From the listed data, it can be observed that these two different theoretical approaches provided similar results.

MAC values are determined by the material's chemical composition (atomic number) as well as energy levels. The weight fractions, densities, and chemical structures of these samples are reported in Table 1. For the energy interaction with matter, there are three types of events that have different impacts on the MAC. The photoelectric effect leads to a diminished MAC in the lower energy region. For analyzed samples, as the energy rises to 0.06 MeV, the MAC values fall significantly. Fig. 2a. illustrates the linear relations between MAC and energy levels. The same is true for the material compositions and variations in the values of MAC. The figure shows that the MAC values have spiked due to the increased energy levels. At low energies, energy interacts with matter the most, and also leads the cross-section of the photoelectric-absorbing-effect as a function of atomic number Z^{4-5} (Kilicoglu, 2019).

At medium energies, the MAC values indicate a marked decline related to Compton Scattering processes. Due to the linear relationship

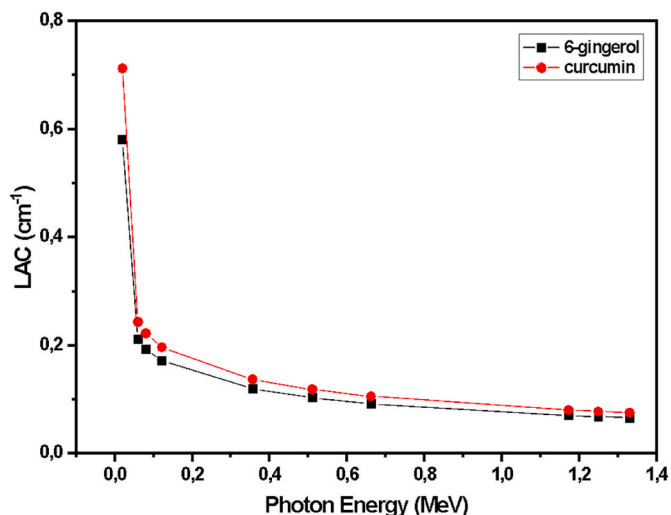


Fig. 2b. Variations of linear attenuation coefficient (LAC) with photon energy for 6-gingerol and curcumin.

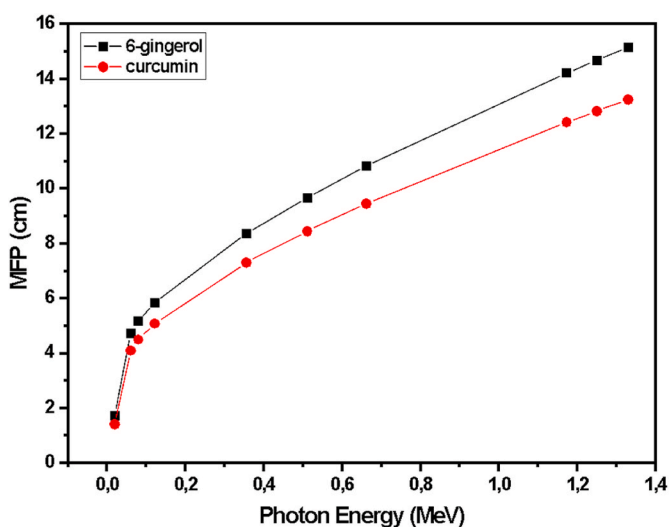


Fig. 2c. Variations of mean free path (MFP) with photon energy for 6-gingerol and curcumin.

between the material's atomic number and the Compton scattering cross-section, MAC values appear to decrease after 0.662 MeV.

The MAC values for all materials of selected samples become constant due to the Compton scattering effect. Because of the linear relationship between cross-sectional Compton scattering and atomic number Z , a line of MAC values appears after 0.662 MeV. MAC values are determined by the chemical composition. Z^{4-5} corresponds to changes in the photoelectric cross-section (Kilicoglu, 2019), and $E^{3.5}$ corresponds to changes in the energy level in reverse (Kilicoglu et al., 2021). For the curcumin sample, the maximum MAC values are recorded. Curcumin has a higher MAC than Gingerol in the studied samples. The findings have shown that the attenuation effects for each form of the sample are greater in the low-energy region.

The LAC between 0.02 and 1.33 are calculated using WinXCOM. The results are represented in Fig. 2b. The chemical composition of the samples, as well as LAC values, are shown to be related to the applied energy. Even though there is an increase in applied energy of up to 1.33 MeV, the MAC values continue to decline. To measure the characteristics and efficiency of attenuation, the LAC values are measured as a function of photon energy (see Fig. 2b). The results revealed that the attenuation

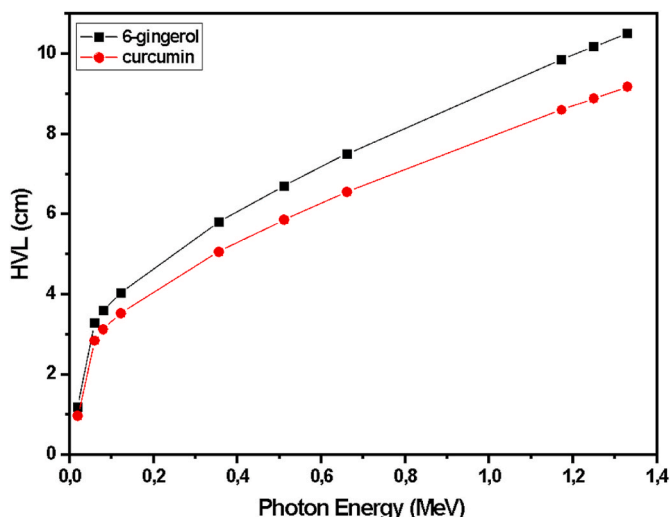


Fig. 2d. Variations of half-value layer (HVL) with photon energy for 6-gingerol and curcumin.

properties of each form of the structure are low in higher energy regions.

The MFP and HVL are the fundamental parameters for calculating the thickness of a material at various photon energies, as well as the substance's attenuation effect. Fig. 2c and Fig. 2d display MFP and HVL. MFP and HVL are variables that should be determined in order to identify the thickness of the samples used in certain photon energies as well as their attenuation efficiency. The sample with the minimum MFP and HVL values seems to have a higher level of protection. A minimum curcumin sample and a high-density sample suppress MFP and HVL while increasing gamma attenuation, as shown in Fig. 2c and d. (Kara et al., 2020; Kilicoglu, 2019).

4. Conclusion

There is limited information on the structural changes that occur in the active components of ginger and turmeric after irradiation. Departing from this, we investigated the physicochemical features of turmeric and ginger following irradiation using a Monte Carlo simulation and empirical testing. On the other hand, several radiation attenuation parameters including mass attenuation, and linear coefficients were also analyzed. According to the results, the density of materials is very effective in the MAC and LAC calculations which are associated with the attributes of materials in terms of low or high absorption of radiation. On the other hand, curcumin showed better absorption attributes compared to 6-gingerol, and it was observed that the total antioxidant capacity of turmeric increased after irradiation treatment which was also supported by the findings indicating an increase in the b (yellowness) value of turmeric after 5 kGy irradiation. Consistent with this finding, positive correlations were found between MAC and ABTS values. This study verifies that the effect of irradiation on the antioxidant activities varied depending on the type of the product. Regarding the total phenolic compounds, it was found that there was a slight decrease after irradiation treatment at 5 kGy dosages for ginger, while a slight increase was observed in turmeric. Considering the fact that the changes that occur after irradiation may depend on the characteristics of the material, further studies are required to better understand the mechanism of action. However, according to the results of this work, it can be concluded that irradiation up to 5 kGy dosages could be beneficial for turmeric as it both prevents microbial contamination and increases its antioxidant activity.

Author statement

Beyza Vahapoglu: Experiment and writing.
 Ozge Kilicoglu: Data Collection, Calculation, Validation, and writing.
 Nur Cebi: Experiment.
 Mehmet Turan Ayseli: Writing.
 Umit Kara: Monte Carlo Simulation.
 Osman Sagdic: Experiment.
 Esra Capanoglu: Experiment and writing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

- Almeida, M.C., Sampaio, G.R., Bastos, D.H.M., Villavicencio, A.L.C.H., 2018. Effect of gamma radiation processing on turmeric: antioxidant activity and curcumin content. *Radiat. Phys. Chem.* 152 (July 2017), 12–16.
- Alothman, M., Bhat, R., Karim, A.A., 2009. Effects of radiation processing on phytochemicals and antioxidants in plant produce. *Trends Food Sci. Technol.* 20 (5), 201–212.
- Apak, R., Güçlü, K., Özyürek, 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. *J. Agric. Food Chem.* 52 (26), 7970–7981.
- Ayseli, M.T., Ayseli, Y.I., 2016. Flavors of the future: health benefits of flavor precursors and volatile compounds in plant foods. *Trends Food Sci. Technol.* 48, 69–77.
- Ayseli, Y.I., Aytekin, N., Buyukkayhan, D., Aslan, I., Ayseli, M.T., 2020. Food policy, nutrition, and nutraceuticals in the prevention and management of COVID-19: advice for healthcare professionals. *Trends Food Sci. Technol.* 105, 186–199.
- Bhandari, U., Sharma, J.N., Zafar, R., 1998. The protective action of ethanolic ginger (*Zingiber officinale*) extract in cholesterol-fed rabbits. *J. Ethnopharmacol.* 61 (2), 167–171.
- Byun, M.W., Yook, H.S., Kim, K.S., Chung, C.K., 1999. Effects of gamma irradiation on physiological effectiveness of Korean medicinal herbs. *Radiat. Phys. Chem.* 54 (3), 291–300.
- Camp, C.H., Cicerone, M.T., 2015. Chemically sensitive bioimaging with coherent Raman scattering. *Nat. Photonics* 9 (5), 295–305.
- Chatterjee, S., Variyar, P.S., Sharma, A., 2009. Stability of lipid constituents in radiation processed fenugreek seeds and turmeric: role of phenolic antioxidants. *J. Agric. Food Chem.* 57 (19), 9226–9233.
- Ellis, D.I., Brewster, V.L., Dunn, W.B., Allwood, J.W., Golovanov, A.P., Goodacre, R., 2012. Fingerprinting food: current technologies for the detection of food adulteration and contamination. *Chem. Soc. Rev.* 41 (17), 5706–5727.
- Ferrara, L., 2019. Nutrition and phytotherapy: a winning combination against headache. *Int. J. Med. Rev.* 6 (1), 6–13.
- Gad, H.A., El-Ahmady, S.H., Abou-Shoer, M.I., Al-Azizi, M.M., 2013. Application of chemometrics in authentication of herbal medicines: a review. *Phytochem. Anal.* 24 (1), 1–24.
- Gölge, E., Ova, G., 2008. The effects of food irradiation on quality of pine nut kernels. *Radiat. Phys. Chem.* 77 (3), 365–369.
- Huang, S.J., Mau, J.L., 2006. Antioxidant properties of methanolic extracts from *Agaricus blazei* with various doses of γ -irradiation. *LWT - Food Sci. Technol. (Lebensmittel-Wissenschaft -Technol.)* 39 (7), 707–716.
- Kara, U., Kilicoglu, O., Ersoy, S., 2020. Structural and gamma-ray attenuation coefficients of different OAD films for nuclear medicine applications. *Radiat. Phys. Chem.* 172 (December 2019), 1–8.
- Khattak, K.F., Simpson, T.J., Ihasnullah, 2008. Effect of gamma irradiation on the extraction yield, total phenolic content and free radical-scavenging activity of *Nigella taiva* seed. *Food Chem.* (4), 967–972.
- Kilicoglu, O., 2019. Characterization of copper oxide and cobalt oxide substituted bioactive glasses for gamma and neutron shielding applications. *Ceram. Int.* 45 (17), 23619–23631.
- Kilicoglu, O., Kara, U., Inanc, I., 2021. The impact of polymer additive for N95 masks on gamma-ray attenuation properties. *Mater. Chem. Phys.* 260 (October 2020), 124093.
- Kim, J.K., Srinivasan, P., Kim, J.H., Choi, J. il, Park, H.J., Byun, M.W., Lee, J.W., 2008. Structural and antioxidant properties of gamma irradiated hyaluronic acid. *Food Chem.* 109 (4), 763–770.
- Lee, J.H., Sung, T.H., Lee, K.T., Kim, M.R., 2004. Effect of gamma-irradiation on color, pungency, and volatiles of Korean red pepper powder. *J. Food Sci.* 69 (8), C585–C592.

- Madhusankha, M., Thilakarathna, C., Navaratne, S., 2018. Analysis of curcumin content in Sri Lankan and Indian turmeric rhizomes and investigating its impact on the colour. *Int. J. Food Sci. Nutr.* 5 (4), 03-05.
- Magdy, A.M., Fahmy, E.M., AL-Ansary, A.E.R.M.F., Awad, G., 2020. Improvement of 6-gingerol production in ginger rhizomes (*Zingiber officinale* Roscoe) plants by mutation breeding using gamma irradiation. *Appl. Radiat. Isot.* 162 (April), 109193.
- Matin, M.A., 2001. Global Trends of Acceptance and Trade in Irradiated Foods. In: Consumers Acceptance and Market Development of Irradiated Food in Asia and the Pacific, Proc. of a Final Research Coordinator Meeting, Bangkok 21- 25 September 1998, IAEA-TECDOC-1219. IAEA, Vienna, pp. 11–16.
- Miller, N.J., Rice-Evans, C.A., 1997. Factors influencing the antioxidant activity determined by the ABTS.+ radical cation assay. *Free Radic. Res.* 26 (3), 195–199. <https://doi.org/10.3109/10715769709097799>.
- Mukisa, I.M., Muyanja, C.M., Byaruhanga, Y.B., Schüller, R.B., Langsrud, T., Narvhus, J. A., 2012. Gamma irradiation of sorghum flour: Effects on microbial inactivation, amylase activity, fermentability, viscosity and starch granule structure. *Radiat. Phys. Chem.* 81 (3), 345–35.
- Oliveira, M.M., Cruz-Tirado, J.P., Barbin, D.F., 2019. Nontargeted analytical methods as a powerful tool for the authentication of spices and herbs: a review. *Compr. Rev. Food Sci. Food Saf.* 18 (3), 670–689.
- Perutka, K., 2010. In: Pereira Leite, Emilson (Ed.), *Tips and Tricks for Programming in Matlab, Matlab - Modelling, Programming and Simulations*. InTech, ISBN 978-953-307-125-1. Available from: <http://www.intechopen.com/articles/show/title/tips-and-tricks-for-programming-in-matlab>.
- Rasool, A., Khan, M., Ali, M.A., Anjum, A.A., Ahmed, I., Aslam, A., Mustafa, G., Masood, S., Nawaz, M., 2017. Anti-avian influenza virus H9N2 activity of aqueous extracts of *Zingiber officinalis* (Ginger) and *Allium sativum* (Garlic) in chick embryos. *Pak. J. Pharm. Sci.* 30 (4), 1341–1344.
- Shao, Y., Tang, F., Xu, F., Wang, Y., Bao, J., 2013. Effects of γ -irradiation on phenolics content, antioxidant activity and physicochemical properties of whole grainrice. *Radiat. Phys. Chem.* 85, 227–233.
- Singleton, V.L., Rossi, J.A.J., 1965. Colorimetry to total phenolics with phosphomolybdic acid reagents. *Am. J. Enol. Viticulture.* 16 (48), 144–158.
- Sirisoontaralak, P., Noomhorm, A., 2007. Changes in physicochemical and sensory-properties of irradiated rice during storage. *J. Stored Prod. Res.* 43 (3), 282–289.
- Song, H.P., Kim, D.H., Jo, C., Lee, C.H., Kim, K.S., Byun, M.W., 2006. Effect of gamma irradiation on the microbiological quality and antioxidant activity of fresh vegetable juice. *Food Microbiol.* 23 (4), 372–378.
- Suhaj, M., Rácová, J., Polovka, M., Brezová, V., 2006. Effect of γ -irradiation on antioxidant activity of black pepper (*Piper nigrum* L.). *Food Chem.* 97 (4), 696–704.
- Taylan, O., Cebi, N., Yilmaz, M.T., Sagdic, O., Ozdemir, D., Balubaid, M., 2021. Rapid detection of green-pea adulteration in pistachio nuts using Raman spectroscopy and chemometrics. *J. Sci. Food Agric.* 101 (4), 1699–1708.
- Teixeira, B.S., Garcia, R.H.L., Takinami, P.Y.L., del Mastro, N.L., 2018. Comparison of gamma radiation effects on natural corn and potato starches and modified cassava starch. *Radiat. Phys. Chem.* 142 (September 2017), 44–49.
- Tulukcu, E., Cebi, N., Sagdic, O., 2019. Chemical fingerprinting of seeds of some salvia species in Turkey by using GC-MS and FTIR. *Foods* 8 (4), 1–12.
- Valizadeh Kiamahalleh, M., Najafpour-Darzi, G., Rahimnejad, M., Moghadamnia, A.A., Valizadeh Kiamahalleh, M., 2016. High performance curcumin subcritical water extraction from turmeric (*Curcuma longa* L.). *J. Chromatogr., B: Anal. Technol. Biomed. Life Sci.* 1022, 191–198.
- Variyar, P.S., Gholap, A.S., Thomas, P., 1997. Effect of γ -irradiation on the volatile oil constituents of fresh ginger (*zingiber officinale*) rhizome. *Food Res. Int.* 30 (1), 41–43.
- Wilson, H.B., Turcotte, L.H., Halpern, D., 2003. *Advanced Mathematics and Mechanics Applications Using MATLAB*, third ed. Chapman & Hall/CRC, United States of America, ISBN 1-58488-262-X.
- Yasmin, K., Arulbalachandran, D., Soundarya, V., Vanmathi, S., 2019. Effects of gamma radiation (γ) on biochemical and antioxidant properties in black gram (*Vigna mungo* L. Hepper). *Int. J. Radiat. Biol.* 95 (8), 1135–1143.