Chapter 8

Effects of Gamma Radiation on Essential Oils: A Review

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Abstract

γ-Radiation provides an effective alternative method to reduce or eliminate microbial contamination of medicinal herbs and other plant materials. However, a search in the literature is important to describe the effects of γ-radiation on the content and integrity of secondary metabolites from plants. The present work provides a review of the effects of γ-radiation on extraction yields and chemical composition of essential oils isolated from roots, rhizome and cortex, leaves, fruits, seeds, flowers, and whole plant. In addition, this review describes the effects of γ-radiation on terpenes. The informations in the present work may assist in research about essential oils and dose of γ-radiation that is able to biologically decontaminate without causing chemical changes in secondary metabolites. These reports in the literature can describe the behavior of many of these metabolites when subjected to various doses of radiation.

Keywords: essential oil, γ-radiation, secondary metabolites, terpenes

1. Introduction

Essential oils (EOs) are plant secondary metabolites, mainly constituted by a mixture of terpenes and terpenoid derivatives (**Figure 1**). Monoterpenes and sesquiterpenes are usually their major constituents [1]. These components are volatile, usually exuding characteristic and pleasant odors. The attraction of insects caused by smell of these essential oils is one of the main factors responsible for the pollination of plants. EOs have many other biological functions, such as protection of plants against diseases caused by fungi and bacteria [2]. Moreover, EOs exhibit a broad spectrum of biological properties, such as mucolytic,

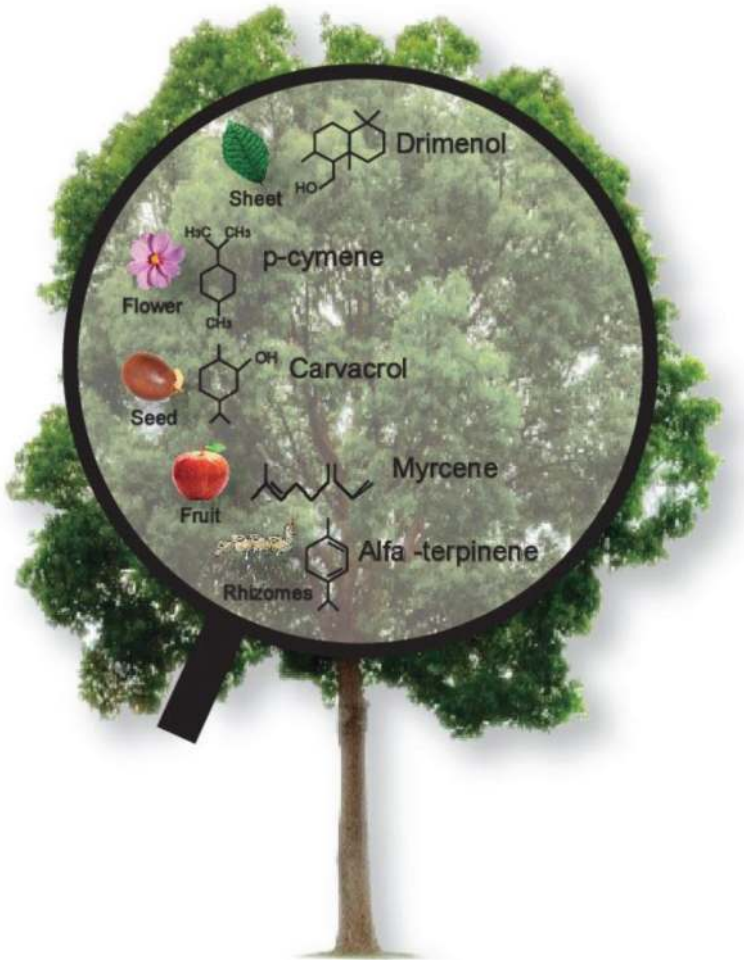

Figure 1. Secondary metabolites present in the different parts of the plant.

expectorant (for example, menthol), and antineoplastic actions [1], stimulating blood flow (for example, EO of mountain pine or common juniper), treatment of gastrointestinal diseases (for example, essential oils of anise, caraway, or fennel), and used in aromatherapy [2]. EOs are also used for production of perfumes and other cosmetic products and are added to foods to improve the flavor [2].

Chemical composition of EOs from plants usually provides important information to its taxonomic identification [3]. However, some environmental factors, such as temperature variation, photoperiod, and light intensity, can influence the biosynthesis of volatile compounds and as a consequence, change its quality and chemical composition [4]. Hydrodistillation is a largely used method in laboratory to obtain EOs from vegetal species. On the other hand, the

most usual and popular method to obtain these chemical constituents is a simple decoction. Pressure, temperature, time, dynamic of extraction, and solvent volume are experimental parameters that influence the extraction efficiency and quality of EOs isolated from natural products [5].

Although EOs obtained from plant materials have important medicinal and industrial applications, herbs rich in EOs are often contaminated with microorganisms. Fungal and bacterial contamination is generally caused by the presence of these microorganisms in soil, water, air, or dust, during harvesting, storage, or processing of herbs [6]. The most usual methods for the microbial decontamination of vegetal material are based on applications of ethylene oxide or methyl bromide. However, both methods promote formation of toxic products and have been banned in many countries, such as Japan and those of the European Union [7].

On the other hand, γ-radiation provides an effective alternative method for reducing or eliminating microbial contamination of medicinal herbs and other vegetal products. This type of radiation of high energy usually passes through skin and soft tissue. A small percentage of γ-radiation is absorbed by cells. Once absorbed by a biological material, γ-radiation can provoke direct and indirect effects at molecular level. Direct effects are responsible for DNA double-strand breaks (DSBs), highly toxic lesions that can cause genetic instability and cell death [8].

Indirect effects are more frequent than direct ones. These effects are caused by the interaction of ionizing radiation with water molecules, generating free radicals. In turn, these free radicals are highly reactive with different cell components, such as DNA, enzymes, and secondary metabolites (including EOs) [7]. Literature describes the effects of γ-radiation on the chemical composition of many vegetal species. Chromatographic analyses of EOs isolated from plant indicated that γ-radiation changes their extraction total yields and chemical compositions. Both the parameters (that is, yields and chemical composition) are mainly influenced by vegetal species, radiation dose, and chemical constituents of the plant material [3]. The present review describes the effects of γ-radiation on the chemical composition of EOs isolated from different plant parts: roots, rhizome and cortex, leaves, fruits, seeds, flowers, and whole plant. One entire section is dedicated for description of the effects of γ-radiation on terpenes.

2. Essential oils from roots

Root samples of *Angelica gigas* Nakai (Danggui) purchased from a local market in Korea were submitted to microbial decontamination using γ-radiation at doses of 1.0, 3.0, 5.0, 10.0, and 20.0 kGy. The extraction yields of its volatile oils were 0.314, 0.313, 0.310, 0.312, and 0.290%, respectively. These values are similar to extraction yield obtained for a nonirradiated sample (yield = 0.313%). The profile of volatile components did not change significantly with radiation [3]. The total content of hydrocarbons and monoterpenes in an irradiated sample (average values considering all irradiated materials = 57.2 and 41.8%, respectively) decreased in relation to a nonirradiated sample (60.00 and 44.14%, respectively). The total content of alcohols, sesquiterpenes, and oxygenated sesquiterpenes in irradiated samples (average

values considering all irradiated materials = 30.3, 4.7, and 18.5%, respectively) was greater than the corresponding nonirradiated sample (23.35, 4.03, and 13.21%, respectively). The total content of monoterpenes α-limonene, *p*-cymene, and camphene in the irradiated samples (average values considering all irradiated materials = 5.2, 1.2, and 4.7%, respectively) are higher in relation to corresponding nonirradiated samples (4.29, 1.07, and 4.10%, respectively). On the other hand, the content of monoterpenes 2,4,6-trimethylheptane and α-pinene in the irradiated samples (average values considering all irradiated materials = 7.9 and 26.9%, respectively) was lower in relation to corresponding nonirradiated samples (13.39 and 30.89%, respectively). The content of oxygenated monoterpenes verbenol, verbenone, α-eudesmol, β-eudesmol, (*E*)-*p*-2-menthen-1-ol, and pinocarveol in irradiated samples (average values considering all irradiated materials = 2.8, 1.8, 2.5, 7.6, 1.5, and 1.4%, respectively) are higher in relation to corresponding nonirradiated samples (2.15, 1.44, 1.90, 5.01, 1.17, and 1.22%, respectively). Irradiated samples showed higher content of the sesquiterpene α-muurolene (average values considering all irradiated materials = 1.9%) than the corresponding nonirradiated samples (1.52%) [3].

Dried root samples of *Glycyrrhiza glabra* Radix (Licorice) collected in Korea were submitted to γ-radiation at doses of 5.0, 10.0, 25.0, and 50.0 kGy. Irradiated samples exhibited higher total content of aldehydes and hydrocarbons (average values considering all irradiated materials = 24.8 and 17.3%, respectively) than the corresponding nonirradiated samples (17.11 and 15.88%, respectively). Irradiated samples exhibited lower total content of alcohols, ketones, and ethers (average values considering all irradiated materials = 12.8, 2.7 and 5.3%, respectively) than the corresponding nonirradiated samples (14.68, 16.08, and 14.4%, respectively). The total sesquiterpene content in nonirradiated and irradiated samples was near 10.0%. The total monoterpene content was near 4.0% in irradiated and nonirradiated samples, except in the sample irradiated at 50.0 kGy that showed monoterpene content near 8.0% [9].

The total content of aldehydes and hydrocarbons from other materials of the same species (roots of *G. glabra*) collected in Korea was higher in irradiated samples at doses of 5.0, 10.0, 25.0, and 50.0 kGy (average values considering all irradiated materials = 42.4 and 26.2%, respectively) than the corresponding nonirradiated sample (28.69 and 11.31%, respectively). The irradiated samples exhibited lower total content of alcohols and ketones (average values considering all irradiated materials = 2.8 and 2.5%, respectively) than the corresponding nonirradiated sample (9.66 and 14.08%, respectively). The total content of monoterpenes in irradiated samples was higher than for a nonirradiated sample. The total content of sesquiterpenes in irradiated samples was lower than for a nonirradiated sample. The identified volatile components were exactly the same in irradiated and nonirradiated samples of *G. glabra* [9].

Dried and powdered roots of *G. glabra* collected in Syria were submitted to γ-radiation at doses of 5.0, 10.0, 15.0, and 20.0 kGy. Higher contents of glycyrrhetinic acid were observed for irradiated samples (average values considering all irradiated materials = 6.1%) than the corresponding nonirradiated sample (4.37%). The content of glycyrrhetinic acid in both irradiated and nonirradiated samples decreased after 12 months of storage [10].

Roots of *Glycyrrhiza uralensis* Fischer collected in Gwangju (South Korea) were irradiated at doses of 1.0, 3.0, 5.0, 10.0, and 20.0 kGy. The content of the major constituents 2-ethoxy-1-propanol,

hexanal, hexanol, *p*-cymen-8-ol, and γ-nonalactone increased in the irradiated samples (average values considering all irradiated materials = 27.1, 6.6, 5.1, 2.4, and 2.6%, respectively) in relation to the nonirradiated sample (22.82, 5.69, 4.78, 2.39, and 2.50%, respectively). However, the content of the constituents ethyl acetate, 4-terpineol, and tetradecanol decreased for irradiated samples (average values considering all irradiated materials = 7.3, 5.8, and 1.7%, respectively) in relation to a nonirradiated sample (7.47, 7.58, and 2.06%, respectively). Benzaldehyde was only detected at a dose of 1 kGy. On the other hand, the compounds 3,5-dimethyl octane and phenethyl alcohol were detected only at a dose of 20 kGy [11].

Samples of *Paeonia albiflora* Pallas var. *trichocarpa* Bunge were submitted to γ-radiation at doses of 1.0, 3.0, 5.0, and 10.0 kGy. Maximum yield of EO was obtained for an irradiated sample at 5 kGy (29.91%). Nonirradiated and irradiated samples at 1.0, 3.0, and 10.0 kGy showed yields of 28.14, 25.89, 26.67, and 25.24%, respectively [1]. Gas chromatography (GC) analysis of volatile compounds obtained from irradiated and nonirradiated samples was similar. A total of 54 compounds was identified in the nonirradiated and irradiated samples at 1.0 kGy. Irradiated samples at 3.0, 5.0, and 10.0 kGy exhibited 55 volatile compounds. This new peak on the GC chromatogram of irradiated samples from 3.0 to 10.0 kGy was attributed to 1,3-bis(1,1-dimethylethyl)-benzene. The highest total contents of alcohols and aldehydes were verified for the irradiated samples (average values considering all irradiated materials = 37.7 and 22.1%, respectively) in relation to the nonirradiated sample (34.26 and 21.44%, respectively). The total contents of acids, esters, furans, ketones, hydrocarbons, and terpenoids were not different among irradiated samples and nonirradiated samples [1].

3. Essential oils from rhizomes and cortices

Ethanol extract of rhizomes of *Cassumunar ginger* purchased in Bangkok was submitted to γ-radiation at doses of 10.0 and 25.0 kGy. EO obtained from nonirradiated and irradiated samples did not show significant changes in the content of sabinene, α-terpinene, γ-terpinene, cymene, α-terpinolene, terpinen-4-ol, α-terpineol, β-sesquiphellandrene, ar-turmerone, ar-curcumene, α-turmerone, β-turmerone, 4-(3′,4′-dimethoxyphenyl)but-3-ene, 4-(3′,4′-dimethoxyphenyl)but-1,-3-ene, (*E*)-1-(3,4-dimethoxylphenyl)butadiene, 4-(2′,4′,5′-trimethoxyphenyl) but-3-ene, and 4-(2′,4′,5′-trimethoxyphenyl)but-1,3-ene [12].

Rhizome samples of *Coptis chinensis* purchased from a local market in Korea were submitted to γ-radiation at doses of 5.0, 10.0, 25.0, and 50.0 kGy. Higher total content of aldehydes and hydrocarbons was verified for irradiated samples (average values considering all irradiated materials = 11.4 and 42.7%, respectively) in relation to nonirradiated samples (7.56 and 35.98%, respectively). Higher total content of sesquiterpene hydrocarbons was verified for irradiated samples at 5.0, 10.0, and 25.0 kGy (average values considering irradiated materials = 47.5, 47.5, and 42.5%, respectively) in relation to nonirradiated sample and irradiated sample at 50.0 kGy (35.0% for both the samples) [9].

Another rhizome sample of *C. chinensis* was purchased from a local market in Korea and irradiated at doses of 5.0, 10.0, 25.0, and 50.0 kGy. The total content of aldehydes in the irradiated

samples (average values considering all irradiated materials = 23.1%) was similar to the non-irradiated samples (23.33%). Higher content of hydrocarbons was verified for the irradiated samples (average values considering all irradiated materials = 16.8%) in relation to the nonirradiated samples (11.21%). The total content of sesquiterpene hydrocarbons was higher in the irradiated sample at 25.0 and 50.0 kGy (20.0% for both the samples) in relation to irradiated samples at 5.0 and 10.0 kGy (15.0% for both the samples) and nonirradiated sample (12.5%) [9].

Rhizome samples of *Curcuma longa* (turmeric) purchased from a local market in Kerala (India) were submitted to γ-radiation at doses of 1.0, 3.0, and 5.0 kGy. Similar extract yields of volatile oils were obtained for irradiated (1.54, 1.70, and 1.43%, respectively) and nonirradiated samples (1.52%). A total of 23 constituents was identified in the nonirradiated and irradiated samples. Significant changes in the concentration of their constituents were not observed for irradiated and nonirradiated samples [13].

Another rhizome sample of *C. longa* that was also purchased from the local market in India was submitted to γ-radiation at 10.0 kGy. The overall yield of volatile oil did not change for the non-irradiated sample (1.71%) and irradiated sample (1.72%). The gas chromatography/mass spectrometry (GC/MS) chromatograms did not indicate significant changes in the concentration of its major constituents: α-phellandrene, *p*-cymene, 1:8-cineol, β-caryophyllene, ar-curcumene, mixture of zingiberene and β-sesquiphellandrene, nerolidol, mixture of ar-turmerone and turmerone, curlone, and dehydrozingerone [8].

Fresh rhizomes samples of *Zingiber officinale* var. *Bangalore* (ginger) purchased from a local market in India were submitted to γ-radiation at a dose of 0.06 kGy. The overall yield of EO was slightly higher for an irradiated sample (0.17%) in relation to a nonirradiated sample (0.14%). The GC/MS chromatograms did not indicate significant changes in the concentration of its major constituents: camphene, β-phellandrene, mixture of linalool and α-terpeniol, neral, geranial, ar-curcumene, nerolidol, mixture of zingiberene and zingiberol, and mixture of β-sesquiphellandrene and β-bisabolene [14].

Cortex bark samples of *Cinnamomum zeylanicum* purchased from a local market in Korea were submitted to γ-radiation at doses of 5.0, 10.0, 25.0, and 50.0 kGy. The content of alcohols and aldehydes (average values considering all irradiated materials = 48.5 and 1.3%, respectively) decreases in relation to a nonirradiated sample (65.02 and 1.61%, respectively). On the other hand, the content of hydrocarbons in the irradiated samples (average values considering all irradiated materials = 29.9%) increased in relation to the nonirradiated sample (15.79%). Higher content of sesquiterpenes was verified for irradiated samples (average values considering all irradiated materials = 30.0%) in relation to nonirradiated samples (17.0%) [9].

Another cortex bark sample of *C. zeylanicum* purchased from a local market in Korea was submitted to γ-radiation at doses of 5.0, 10.0, 25.0, and 50.0 kGy. The total content of alcohols, aldehydes, and hydrocarbons increased in irradiated samples (average values considering all irradiated materials = 1.8, 76.5, and 14.9%, respectively) in relation to the nonirradiated sample (1.66, 79.31, and 11.71%, respectively). Higher total content of sesquiterpenes was verified for irradiated samples at 25.0 and 50.0 kGy (17.5% for both the samples) in relation to nonirradiated sample and irradiated samples at 5.0 and 10.0 kGy (near 15.0% for both the samples) [9].

4. Essential oils from leaves

Leaf samples of *Echinodorus macrophyllus* purchased from the local market in Belo Horizonte (Brazil) were submitted to γ-radiation at doses of 1.0, 3.0, 5.0, 10.0, and 20.0 kGy. The overall yield of EO extracted from irradiated leaves (0.67, 0.46, 0.72, 0.58, and 0.418%, respectively) was higher than the corresponding yield for nonirradiated samples (0.27%) [15]. The total content of acyclic monoterpenes and sesquiterpene derivatives in irradiated samples (average values considering all irradiated materials = 0.3 and 3.1%, respectively) was increased in relation to nonirradiated samples (0.11 and 1.90%, respectively). On the other hand, the total content of the other chemical classes, such as triterpenes, diterpenes, esters, and carotenoid derivatives, in irradiated samples (average values considering all irradiated materials = 0.7, 2.7, 76.1, and 3.3%, respectively) was lightly decreased in relation to nonirradiated sample (0.99, 2.93, 79.68, and 4.26%, respectively). Irradiated samples exhibited higher content of linalool, α-caryophyllene, drimenol, hexahydrofarnesyl acetone, (*E*,*E*)-farnesyl acetone, ethyl hexadecanoate, methyl (*Z*,*Z*)-9,12-octadecadienoate, and methyl (*E*,*E*,*E*)-11,14,17-eicosatrienoate (average values considering all irradiated materials = 0.3, 0.7, 1.5, 0.9, 1.4, 1.9, 2.3, and 11.3%, respectively) in relation to nonirradiated sample (0.11, 0.22, 0.66, 0.40, 0.93, 1.22, 1.70, and 7.94%, respectively). On the other hand, the content of dihydroedulan, β-caryophyllene, methyl hexadecanoate, ethyl (*Z*,*Z*,*Z*)-9,12,15-octadecatrienoate, squalene (average values considering all irradiated materials = 0.9, 0.5, 40.0, 6.8, and 0.7%, respectively) exhibited lower relative content when the samples were not exposed to γ-radiation (2.9, 0.8, 44.3, 12.7, and 1.0%, respectively). The samples submitted to γ-radiation did not exhibit significant changes in the content of 10-(acetylmethyl)-(+)-3-carene, (*E*)-nerolidol, methyl (*Z*,*Z*,*Z*)-9,12,15-octadecatrienoate, (*E*)-phytol, methyl octadecanoate, ethyl (*Z*,*Z*,*Z*)-9,12,15-octadecatrienoate, and ethyl octadecanoate [15].

Leaf samples of *Eucalyptus radiata* purchased from a local market of Tilman (Belgium) were submitted to γ-radiation at a dose of 25.0 kGy. The overall yield of volatile oil did not change for nonirradiated (0.84%) and irradiated samples (0.85%). Both the samples did not exhibit significant differences in the content of α-pinene, eucalyptol, β-myrcene, terpinen-4-ol, sabinene, neral, α-terpineol, linalyl acetate, and β-bisabolone, which were the major constituents identified in its EO [16].

Leaf samples of *Mentha piperita* L. (a natural hybrid between *Mentha spicata* L. and *Mentha aquatica* L.) were submitted to γ-irradiation at doses of 10.0 and 25.0 kGy. The overall yield of EO for nonirradiated and irradiated samples was similar (0.9%). Irradiated samples exhibited changes in the content of menthol and menthone (average values considering all irradiated materials = 51.6 and 14.5%, respectively) in relation to the nonirradiated sample (52.4 and 13.8%, respectively). Irradiated samples exhibited similar content of γ-gurjunene, *neo*-menthol, α-terpinene, α-gurjunene, *neo*-isomenthol 1,8-cineole, and isopulegol, in irradiated samples (average values considering all irradiated materials = 1.4, 6.4, 0.4, 8.8, 6.4, 3.7, and 1.0%, respectively) in relation to the nonirradiated sample (1.4, 6.5, 0.5, 8.9, 6.5, 3.9, and 0.8%, respectively) [17].

Leaf samples of *M. piperita* purchased in Marrakesh (Morocco) were submitted to γ-radiation at a dose of 1.0 kGy. Some differences were observed in the composition of the EO for irradiated and nonirradiated samples. Higher contents of carvone and dihydrocarveol in the

irradiated sample (35.88 and 6.95%, respectively) were verified in relation to the nonirradiated sample (31.83 and 3.14%, respectively). Some nonidentified constituents (GC retention times at 5.67, 5.83, and 6.73 min) exhibited a slight increase for the irradiated sample. The content of viridiflorol, carvacrol, carvyl acetate, and D-germacrene was only detected on the GC chromatogram of the nonirradiated sample (5.35, 3.28, 1.30, and 1.25%, respectively). The content of 1,8 cineole, dihydrocarvyl acetate, and a-bourbonene was similar for both the samples [18].

Leaf samples of *Ocimum basilicum* purchased from the local market in São Paulo (Brazil) were submitted to γ-radiation at doses of 10.0, 20.0, and 30.0 kGy. Chromatographic analysis indicated no significant differences between nonirradiated and irradiated samples [19].

The other leaf sample of *O. basilicum* purchased from a local market in Copenhagen (Denmark) was irradiated using doses of 3.0, 10.0, and 30.0 kGy. The content of 1,8 cineole, β-caryophyllene, methylchavicol, methyleugenol, and linalool also did not exhibit significant differences between nonirradiated and irradiated samples [20].

A third work employing irradiated leaves of *O. basilicum* purchased from Egypt was performed using doses of 5.0 and 10.0 kGy. The content of α-cubebene, an isomer of cadinene, eremophyllene, myristicine, α-pinene, camphene, myrcenol, α-terpineol, allylphenol, safrole, methyl eugenol, and β-bisabolene did not change after exposition to irradiation. However, a significant increase was observed in the content of linalool, estragole, *p*-cymene, 1,8-cineole, *cis*-linalool oxide, *cis*-methyl cinnamate, thymol, β-phellandrene, β-pinene, β-myrcene, γ-terpinene, *cis*-*p*-2-menthen-1-ol, and neral for irradiated samples (average values considering all irradiated materials = 27.7, 13.4, 0.2, 6.2, 0.2, 1.2, 2.4, 0.3, 0.6, 0.2, 0.1, 0.4, and 0.3%, respectively) in relation to the nonirradiated sample (14.92, 4.54, 0.03, 5.14, 0.08, 0.66, 0.68, 0.18, 0.46, 0.10, 0.01, 0.21, and 0.18%, respectively). On the other hand, a decrease was observed for the content of *trans*-methyl cinnamate, α-bergamotene, an isomer of cubebene, β-farnesene, γ-cadinene, calamenene, α-caryophyllene, β-caryophyllene, camphor, borneol, terpin-1-en-4-ol, eugenol, spathulenol, δ-cadinol, and α-cadinol when the samples were exposed to radiation (average values considering all irradiated materials = 5.4, 5.7, 1.8, 0.5, 2.6, 0.3, 0.6, 0.9, 0.3, 0.3, 0.7, 10.1, 0.7, 0.7, and 5.3%, respectively) in relation to the nonirradiated sample (9.08, 6.88, 2.42, 0.77, 3.77, 2.31, 0.73, 1.24, 1.41, 0.72, 0.88, 12.13, 1.04, 1.28, and 9.89, respectively) [21].

Leaf samples of *Origanum vulgare* collected in Turkey were submitted to γ-radiation at doses of 5.0, 7.5, 10.0, and 30.0 kGy. The majority of the identified volatile constituents was only slightly affected by the radiation. Irradiated sample at 5.0 kGy did not exhibit changes in relation to nonirradiated sample. Irradiated sample at 10.0 kGy exhibited a significant increase of the content of linalool, hotrienol, sabinen hydrate, *p*-methoxypyridine, α-terpinolene, and two linalool oxide derivatives. Irradiated sample at 30.0 kGy exhibited a significant increase of *p*-methoxypyridine, α-terpinolene, and both the linalool oxide derivatives. On the other hand, a decrease of bicyclogermacrene was observed for irradiated samples [22].

Leaves of *O. vulgare L.* collected in Santiago Valley (Chile) were submitted to γ-radiation at 1.0, 2.0, 3.0, 5.0, 10.0, and 15.0 kGy. The overall yield of EOs obtained by steam distillation was not different for irradiated and nonirradiated samples. The content of α-pinene, sabinene, myrcene, *p*-cymene, ocimene, *cis*-β-terpineol, carvacryl methyl ether, linalyl propionate, thymol, carvacrol, spathulenol, and caryophyllene oxide increased when the samples were exposed to

radiation. However, the content of β-phellandrene, α-terpinene, γ-terpinene, *trans*-sabinene hydrate, terpinolene, *cis*-*p*-2-menthen-1-ol, δ-4-carene, l-borneol, terpinen-4-ol, and piperitol decreased for irradiated samples. Moreover, the CG chromatogram registers an increase of unidentified peaks at doses higher than 5.0 kGy. These peaks are registered at higher retention times than the identified volatile components [23].

Leaf samples of *Thymus vulgaris* L. purchased in Ankara (Turkey) were submitted to γ-radiation at doses of 7.0, 12.0, and 17.0 kGy. Irradiated and nonirradiated samples did not exhibit significant changes on the content of limonene, 1,8-cineole, linalool, borneol, terpinen-4-ol, α-terpineol, thymol, carvacrol, β-caryophyllene, caryophyllene oxide, α-terpinene, γ-terpinene, and *p*-cimene. The content of cumin aldehyde was increased for the samples irradiated at 17.0 kGy (0.6%) in relation to the nonirradiated sample (0.08%). The content of myrcene was not detected in the sample irradiated at a dose of 17.0 kGy [24].

Leaf samples of *T. vulgaris thymoliferum* purchased in Tilman (Belgium) were submitted to γ-radiation at a dose of 25.0 kGy. Overall yield of the volatile oils obtained from nonirradiated and radiated samples was similar (1.11 and 1.12%, respectively). The content of α-pinene, β-pinene, myrcene, *p*-cymene, γ-terpinene, linalool, terpinen-4-ol, *cis*-geraniol, thymol, carvacrol, β-caryophyllene, and in caryophyllene oxide in irradiated samples was also similar to the corresponding nonirradiated sample [16].

Other leaf samples of *T. vulgaris* purchased in Copenhagen (Denmark) were submitted to γ-radiation at doses of 3.0, 10.0, and 30.0 kGy and after being stored for a period of one month. The content of α-thujene, α-pinene, myrcene, α-terpinene, *p*-cymene, *trans*-sabinene hydrate, linalol, borneol, thymbol, carvacrol, β-caryophyllene, and caryophyllene oxide did not exhibit changes among irradiated and nonirradiated samples. The content of γ-terpinene in irradiated samples (average values considering all irradiated materials = 0.101%) was slightly higher in relation to the nonirradiated sample (0.098%) [25].

Dried samples of *Allium fistulosum* L. (Welsh onion) collected in Gwangju (South Korea) were submitted to γ-radiation at doses of 1.0, 3.0, 5.0, 10.0, and 20.0 kGy. The content of 2-methyl-2-pentenal, methyl propyl trisulfide, propylene sulphide, and 1-propane-1-thiol increased for the irradiated samples (average values considering all irradiated materials = 12.0, 8.5, 6.3, and 4.5%, respectively) in relation to the nonirradiated sample (6.07, 4.67, 5.37, and 3.92%, respectively). However, a significant decrease was observed in the content of dipropyl trisulfide, 1-propanethiol, 3,5-diethyl-1,2,4-trithiolane, (*E*)-propenyl propyl disulfide, and (*Z*)-propenyl propyl disulphide (average values considering all irradiated materials = 7.4, 11.8, 1.3, 4.2 and 3.4%, respectively) in relation to the nonirradiated sample (23.77, 16.33, 7.31, 7.59, and 6.02%, respectively). Moreover, nonanal was not detected in the nonirradiated sample, but it was detected at a dose of 3.0 kGy [26].

5. Essential oils from fruits

Fruit samples of *Carica papaya* were submitted to γ-radiation at doses from 0.05 to 3.0 kGy. The GC chromatogram of the irradiated samples exhibited a new peak that was identified

as phenol. The content of phenol in different irradiated samples exhibited a dose-dependent increase with radiation, being linear in the dose range of 0.1–3.0 kGy [27].

Fruit samples of *Citrus paradise* (grape fruits) were collected in Texas (USA), and 3 days after harvest, the samples were submitted to γ-radiation at doses of 0.15 and 0.30 kGy. Pulp of non-irradiated fresh grape fruits exhibited higher content of D-limonene and myrcene (10.00 and 0.27%, respectively) than fruits exposed to radiation at 0.15 kGy (6.00 and 0.17%, respectively). However, irradiated sample at 0.3 kGy did not exhibit significant changes of D-limonene and myrcene in relation to nonirradiated sample [28].

A sample of grape fruit variety (Rio Red) collected in Texas (USA) was submitted to γ-radiation at doses of 0.00, 0.07, 0.20, 0.40, and 0.70 kGy. The content of β-carotene, limonin-β-D-glucopyranoside, and total carotenoids did not exhibit changes between irradiated and non-irradiated samples. A total of 35 days after harvest, fruit samples exposed to radiation at 0.07 kGy exhibited higher content of lycopene (1.53%) than fruits exposed to 0.70 kGy (1.32%) [29].

Peel samples of *Citrus unshiu* purchased from a local market in Korea were submitted to γ-radiation at doses of 5.0, 10.0, 25.0, and 50.0 kGy. The total content of acids and alcohols increased in irradiated samples (average values considering all irradiated materials = 8.4 and 6.7%, respectively) in relation to nonirradiated sample (6.43 and 5.46%, respectively). On the other hand, the total content of aldehydes and hydrocarbons decreased in irradiated samples (average values considering all irradiated materials = 21.6 and 52.1%, respectively) in relation to the nonirradiated sample (26.38 and 54.35%, respectively). Higher total content of sesquiterpene hydrocarbons was verified for irradiated samples at 25.0 and 50.0 kGy (5.0% for both the samples) in relation to nonirradiated and irradiated samples at 10.0 and 5.0 kGy (2.5% for each sample). Higher total content of monoterpene hydrocarbons was verified for nonirradiated and irradiated samples at 5.0 and 10.0 kGy (50.0% for each sample) in relation to irradiated sample at 25.0 and 50.0 kGy (45.0% for both the samples. The content of limonene and α-terpineol decreased for increasing radiation doses [9].

Another peel sample of *C. unshiu* purchased from a local market in Korea was submitted to γ-radiation at doses of 5.0, 10.0, 25.0, and 50.0 kGy. The total content of acids, alcohols, and aldehydes increased for the irradiated samples (average values considering all irradiated materials = 6.3, 6.2, and 14.1, respectively) in relation to nonirradiated sample (5.79, 5.87, and 10.80%, respectively). On the other hand, the total content of hydrocarbons decreased in the irradiated samples (average values considering all irradiated materials = 58.7%) in relation to nonirradiated sample (62.30%). Higher total content of sesquiterpene hydrocarbons was verified for irradiated samples at 10.0 and 25.0 kGy (32.5% for both the samples) in relation to nonirradiated and irradiated samples at 5.0 and 50.0 kGy (28.0% for each sample). Higher total content of monoterpene hydrocarbons was verified in nonirradiated and irradiated samples at 5.0 and 25.0 kGy (35.0% for each sample) in relation to average values considering all the irradiated materials = 25.0% for both the samples). The content of limonene and α-terpineol decreased for increasing radiation doses [9].

Volatile extract of *Maroc late* (Mature oranges) harvested in Morocco was submitted to γ-irradiation at doses of 1.0 and 2.0 kGy. GC analysis did not indicate significant differences

between nonirradiated and irradiated samples at 1.0 kGy. Irradiated fruits at 2.0 kGy exhibited lower content of linalool, citral, and methyl anthranilate (0.59, 0.16, and 0.08%, respectively) in relation to the corresponding content of nonirradiated sample (0.80, 0.24, and 0.13%, respectively). On the other hand, the content of D-limonene (94.17%) was higher than the corresponding content for nonirradiated samples (93.70%) [30].

Fruit samples of *Piper guineense* purchased from a local market in Eziama Ikeduru (Nigeria) were exposed to γ-radiation at a dose of 10.0 kGy. The content of *p*-cymenol was slightly increased in the irradiated sample (0.19%) in relation to nonirradiated sample (0.05%). The content of α-pinene, camphene, β-pinene, sabinene, myrcene, limonene, phellandrene, 1-8-cineole, ocimene, γ-terpinene, β-cymene, terpinolene, *cis*-linalool oxide, α-cubebene, δ-elemene, α-ylangene, camphor, linalool, gurjunene, *p*-caryophyllene, γ-elemene, cardene, epi-β-farnesene, (*Z*)-β-farnesene, humulene, (*E*)-β-farnesene, germacrene-D, zingiberene, himachalene, β-selinene, bicyclogermacrene, δ-cadinene, sesquiphellandrene, cadina-1,4-diene, calamenene, *p*-cymene-ol, α-calacorene, caryophyllene oxide, methyl eugenol, nerolidol, elemol, guaiol, γ-cadinol, bisabolol, β-eudesmol did not exhibit change when the sample was exposed to γ-radiation [31].

Fruit samples of *Piper nigrum* purchased from a local market in Ankara (Turkey) were submitted to γ-radiation at doses of 7.0, 12.0, and 17.0 kGy. The overall yield of EO decreased for the irradiated samples at 17.0 kGy in relation to the nonirradiated sample. Higher content of γ-terpinene and thymol (average values considering all irradiated materials = 0.64, and 0.50%, respectively) was verified for irradiated samples in relation to the nonirradiated sample. Higher content of cumin aldehyde was verified for irradiated samples at 12.0 and 17.0 kGy (14.73 and 8.30%, respectively) in relation to the nonirradiated sample (0.85%). Higher content of carvacrol, caryophyllene oxide, and *p*-cymene was verified for irradiated sample at 17 kGy (1.85, 2.15, and 0.67%, respectively) in relation to the nonirradiated sample (0.30, 0.94, and 0.34%, respectively). The smaller content of β-selinene was verified for irradiated samples at 12.0 and 17.0 kGy (5.42 and 5.81%, respectively) in relation to the nonirradiated sample (6.88%). The smaller content of methyleugenol, α-gurjunene, and valencene was verified for irradiated sample at 12.0 kGy (2.59, 0.17, and 5.82%, respectively) in relation to the nonirradiated sample (3.33, 0.37, and 7.33%, respectively). The content of α-pinene, β-pinene, myrcene, α-phellandrene, δ-3-carene, limonene, linalool, δ-elemene, α-cubebene, β-caryophyllene, α-caryophyllene, cadinene, spathulenol, (−)-aristolene, and (+)(*E*)-bicyclosesquiphellandrene did not exhibit changes between irradiated and nonirradiated samples [24].

Dried berry samples of *P. nigrum* purchased from a local market in Mäspoma (Slovak Republic) were submitted to γ-radiation at doses of 5.0, 10.0, and 30.0 kGy. The qualitative compositions of their volatile oils were similar for nonirradiated and irradiated samples. The content of their constituents did not exhibit significant change for nonirradiated and irradiated samples at 5.0 and 10.0 kGy. However, lower content of β-elemene, α-guaiene, α-humulene, and β-farnesene was verified for samples irradiated at 30.0 kGy. On the other hand, higher content of *trans*-sabinene hydrate, 3,4-dimethylstyrene, cyclohexenol, *p*-cymen-8-ol, terpinen-4-ol, α-terpineol, α-terpineol, eucarvone, piperitenone, piperitone, undecanone, and spathulenol

was verified for irradiated samples at 30.0 kGy. The most significant change was observed for irradiated sample at 30.0 kGy, which exhibit an increase of caryophyllene oxide and a proportional decrease of β-caryophyllene in relation to nonirradiated sample [32].

Another sample of black pepper purchased from a local market in Cairo (Egypt) was submitted to γ-radiation at doses of 5.0 and 10.0 kGy. GC analysis of the nonirradiated sample indicated 21 constituents, while the corresponding irradiated samples indicated 16 and 15 constituents for irradiated samples at 5.0 and 10.0 kGy, respectively. The content of α-thujene, Me-chavicol, and Me-salicylic (average values considering all irradiated materials = 4.4, 3.0, and 0.6%, respectively) increased for irradiated samples in relation to nonirradiated sample (1.36, 1.57, and 0.10%, respectively). The content of α-pinene, β-pinene, α-phellandrene, mixture of β-phellandrene and limonene, geraniol, cymene, terphenyllin, and β-caryophyllene in irradiated samples (average values considering all irradiated materials = 0.2, 1.0, 0.5, 35.8, 1.9, 0.6, 0.5, and 1.5%, respectively) decreased in relation to nonirradiated samples (1.04, 6.32, 3.42, 39.92, 15.54, 0.72, 0.73, and 3.67%, respectively). Myrcene and α-terpinene were not detected in samples exposed at a dose of 5.0 kGy. However, higher content of myrcene and α-terpinene was verified for irradiated samples at a dose of 10.0 kGy (0.9 and 2.6%, respectively) when compared to nonirradiated sample (0.64 and 2.06%, respectively). Terpinol and anisole were not detected at 10.0 kGy. However, both the constituents exhibit higher content at 5.0 kGy (6.89 and 0.60%, respectively) in relation to nonirradiated sample (6.59 and 0.57%, respectively). Undecanal was not detected at 10.0 kGy, and this constituent exhibited lower concentration at 5.0 kGy (0.19%) in relation to nonirradiated sample (1.01%). The content of eugenol was decreased at 5.0 kGy (1.10%) and increased at 10.0 kGy (2.02%) when compared with the nonirradiated sample (1.23%) [33].

Immature fruit samples of *Poncirus trifoliata* (poncirin) purchased from a local market in Korea were submitted to γ-radiation at doses of 5.0, 10.0, 25.0, and 50.0 kGy. The total content of alcohols, aldehydes, and hydrocarbons decreased in irradiated samples (average values considering all irradiated materials = 2.3, 1.1, and 47.0%, respectively) in relation to nonirradiated sample (3.42, 3.38, and 48.82%, respectively). The higher total content of sesquiterpene hydrocarbons was verified for irradiated samples at 50.0 kGy (40.0%) in relation to nonirradiated sample and irradiated samples at 5.0 and 25.0 kGy (37.5% for both the samples) and in relation to irradiated sample at 10 kGy (35.0%). The higher total content of monoterpene hydrocarbons was verified for the irradiated sample at 10.0 kGy (15.0%) and nonirradiated sample and irradiated sample at 5.0 kGy (10.0%) in relation to irradiated samples at 25.0 and 50.0 kGy (5.0% for both the samples). The content of limonene and α-terpineol decreased for increasing radiation doses [9].

Another immature fruit sample of *P. trifoliate* purchased from a local market in Korea was submitted to γ-radiation at doses of 5.0, 10.0, 25.0, and 50.0 kGy. The total content of alcohols, aldehydes, and hydrocarbons increased in irradiated samples (average values considering all irradiated materials = 2.0, 21.9, and 35.2%, respectively) in relation to nonirradiated sample (1.83, 19.77, and 32.72%, respectively). The higher total content of sesquiterpene hydrocarbons was verified for irradiated samples at 5.0 and 25.0 kGy (32.5% for both the samples) and at 10.0 and 50.0 kGy (30.0% for both the samples) in relation to nonirradiated sample

(27.5%). The total content of monoterpene hydrocarbons was similar between irradiated and nonirradiated samples (5.0% for both the samples). The content of limonene and α-terpineol decreased for increasing radiation doses [9].

6. Essential oils from seeds

Seed samples of *Prunus armeniaca* (apricot kernel) purchased from a local market in Korea were submitted to γ-radiation at doses of 5.0, 10.0, 25.0, and 50.0 kGy. The total content of acids, aldehydes, and hydrocarbons (average values considering all irradiated materials = 2.9, 19.4, and 26.3%, respectively) increased in irradiated samples in relation to nonirradiated sample (2.81, 19.12, and 17.27%, respectively). The total content of sesquiterpene hydrocarbons was higher for samples exposed to 25.0 and 50.0 kGy (37.5 and 27.5%, respectively) in relation to nonirradiated and irradiated samples at 5.0 and 10.0 kGy (15% for each sample) [9].

Other samples of *P. armeniaca* purchased from a local market in Korea were submitted to γ-radiation at doses of 5.0, 10.0, 25.0, and 50.0 kGy. The total content of alcohols and aldehydes decreased in irradiated samples (average values considering all irradiated materials = 2.1 and 20.9%, respectively) in relation to nonirradiated sample (2.29 and 37.46%, respectively). The total content of hydrocarbons increased in irradiated samples (average values considering all irradiated materials = 38.0%) in relation to nonirradiated sample (33.48%). The total content of sesquiterpene hydrocarbons was higher in irradiated samples at 10.0 and 50.0 kGy (35.0% for both the samples) in relation to nonirradiated sample and irradiated samples at 5.0 and 25.0 kGy (32.5% for each sample). The chromatographic profiles were almost identical in nonirradiated samples and in samples irradiated at low doses (5.0 and 10.0 kGy). However, irradiated samples at higher doses (from 25.0 to 50.0 kGy) exhibited different chromatographic profiles in relation to the nonirradiated sample. Three other volatile hydrocarbons were detected on the GC chromatogram of the samples irradiated at 10.0, 25.0, and 50.0 kGy, which were identified as 1,7,10-hexadecatriene, 6,9-heptadecadiene, and 8-heptadecene [9].

Seed samples of *Cuminum cyminum* L. purchased from a local market in Ankara (Turkey) were submitted to γ-radiation at doses of 7.0, 12.0, and 17.0 kGy. The higher content of cumin aldehyde was verified for irradiated samples (average values considering all irradiated materials = 64.1%) in relation to the nonirradiated sample (59.75%). The content of carvacrol increased in the irradiated sample at 17.0 kGy (1.55%) in relation to the nonirradiated sample (0.47%). The smaller content of α-phellandrene and γ-terpinene was verified for irradiated samples (average values considering all irradiated materials = 0.2 and 4.6%, respectively) in relation to the nonirradiated sample (0.40 and 10.31%, respectively). The smaller content of limonene was verified for irradiated samples at 12.0 and 17.0 kGy (average values considering all irradiated materials = 0.13%) in relation to nonirradiated sample (0.46%). The content of β-pinene decreased in irradiated sample at 17.0 kGy (1.02%) in relation to nonirradiated sample (3.63%). The content of *p*-cimene, 1,8-cineole, linalool, α-terpineol, phellandral, safranal, β-gurjunene, β-caryophyllene, β-farnesene, p-cimene, linalool, acoradiene, γ-terpinene, and carotol did not change when the samples were exposed to γ-radiation [24].

Seed samples of *C. cyminum* purchased from Iran were also submitted to γ-radiation at doses of 10.0 and 25.0 kGy. The overall yield of EO from irradiated and nonirradiated seed samples was similar (1.5% for each sample). The content of α-terpinen-7-al, γ-terpinen-7-al, and sabinene decreased in the irradiated samples (average values considering all irradiated materials = 0.1, 18.5, and 0.6%, respectively) in relation to nonirradiated sample (0.21, 21.48, and 0.64%, respectively). The content of α-thujene and β-pinene slightly increased in irradiated samples (average values considering all irradiated materials = 0.3 and 24.7%, respectively) in relation to nonirradiated sample (0.21 and 24.07%, respectively). The content of cumin aldehyde, *p*-cymene, and α-pinene decreased in sample irradiated at 10.0 kGy (17.98, 10.20, and 1.03%, respectively) in relation to the nonirradiated sample (19.03, 10.20, and 1.03%, respectively), and the content of these compounds increased in irradiated sample at 25.0 kGy (20.51, 17.75, and 1.12, respectively). The content of myrcene and γ-terpinene increased in irradiated sample at 10.0 kGy (0.85 and 21.91%, respectively) in relation to the nonirradiated sample (0.73 and 20.09, respectively), and the content of these compounds decreased in irradiated sample at 25.0 kGy (nondetected and 15.46%, respectively) [34].

Seed samples of *Salvia sclarea* L. (clary sage) purchased from Konya (Turkey) were submitted to γ-radiation at doses of 2.5, 4.0, 5.5, and 7.0 kGy. Irradiated samples exhibited a decrease in the content of β-pinene, limonene, α-terpineol, and amyl alcohol (average values considering all irradiated materials = 9.8, 11.1, 5.3, and 2.5%, respectively) in relation to nonirradiated sample (18.81, 15.60, 6.54, and 4.82%, respectively). On the other hand, the content of 1,4-dichlorobenzene, 2-ethyl-1-hexanol, and linalool increased for an irradiated sample at 2.5 kGy (19.33, 15.59, and 9.05%, respectively) in relation to a nonirradiated sample (14.74, 14.34, and 7.98, respectively). The content of 1-hexanol also increased for a sample irradiated at 5.5 kGy (11.22%) in relation to a nonirradiated sample (10.29%). Compounds 2,2,4,6,6-pentamethylheptane and 2,2-dimethylundecane were only detected in nonirradiated samples (4.02 and 2.86%, respectively) [35].

Seed samples of *Monodora myristica* were submitted to γ-radiation at 15.0 kGy. The effects of γ-radiation on the EO were not significant. The most remarkable change was observed for α-thujene and β-cymene. The content of these monoterpenes in the irradiate sample (16.76 and 9.29%, respectively) was higher than to the nonirradiated sample (7.14 and 7.14%, respectively). On the other hand, terpinolene, α-terpineol, α-cubebene, and caryophyllene were only detected in small amounts in the nonirradiated sample [36].

Seed samples of *Linum usitatissimum* (linseed) were submitted to γ-radiation at doses of 2.5, 4.0, 5.5, and 7.0 kGy. Irradiated samples at 2.5 and 4.0 kGy decreased the content of *p*-xylene, limonene, and styrene in relation to the nonirradiated sample. The content of 1-hexanol, *p*-xylene, and limonene increased in the irradiated sample at 5.5 kGy. Compounds *p*-cymene, benzaldehyde, and nonanol were not detected in the irradiated samples [37].

7. Essential oils from flowers

Dried flower samples of *Lavandula angustifolia* purchased from Tilman (Belgium) were exposed to γ-radiation at a dose of 25.0 kGy. Overall yield of EO from irradiated sample was

similar to the corresponding yield for the nonirradiated sample (0.44%). Nonirradiated and irradiated samples exhibited similar qualitative composition of *p*-cymene, *trans*-*β*-ocimene, *cis*-*β*-ocimene, linalool, lavandulol, hexyl acetate, linalyl acetate, *β*-farnesene, neryl acetate, *β*-caryophyllene, borneol, caryophyllene oxide, and geranyle acetate [16].

Flower samples of *Crocus sativus* L. purchased from Srinagar (India) were exposed to *γ*-radiation at a dose of 5.0 kGy. Overall yield of EO from irradiated sample was similar to the corresponding yield of the nonirradiated sample (0.6%). The content of safranal; 2,6,6-trimethyl-4-hydroxy-1-cyclohexene-1-carboxaldehyde; 2,6,6-trimethyl-1,4-cyclohexadione; 3,5,5-trimethyl-2-hydroxy-1,4-cyclohexadione-2-ene; 2,5-dimethyl-2-isopropenyl-l-cyclohexanone; 2,4,4-trimethyl-3-carboxaldehyde-5-hydroxy-1-cyclohexanone 2,5-diene; and dihydro-beta-ionene obtained from the irradiated sample (19.56, 0.63, 1.78, 1.22, 0.34, 2.8, and 3.43%, respectively) decreased in relation to the nonirradiated sample (32.93, 1.57, 1.81, 1.67, 0.35, 3.4, and 3.71%, respectively). The content of *α*-isophorone, ketoisophorone, and 2,4-cycloheptadiene-1-one-2,6,6-trimethyl (6.17, 3.48, and 1.92%, respectively) increased in relation to the nonirradiated sample (5.25, 3.17, and 1.85%, respectively) [38].

Flower samples of *Solanum stipulaceum* collected in Montes Claros (state of Minas Gerais, Brazil) were exposed to *γ*-radiation at doses of 1.0, 2.5, 5.0, 10.0, and 20.0 kGy. The yield of volatile oil obtained from nonirradiated flowers was slightly increased by *γ*-radiation. The content of *α*-copaene, *β*-elemene, *β*-caryophyllene, *α*-humulene, and aromadendrene increased with radiation except when the plant material was exposed at a dose of 20 kGy. The content of *δ*-cadinene, caryophyllene oxide, and alloaromadendrene oxide-(2) increased with *γ*-radiation. The content of D-germacrene, *γ*-gurjunene, and 7-epi-*α*-cadinene decreased with *γ*-radiation in relation to the nonirradiated sample [39].

8. Essential oils from buds

Bud-fermented samples of *Camellia sinensis* (oolong tea) purchased from a local market in São Paulo (Brazil) were exposed to *γ*-radiation at doses of 5.0, 10.0, 15.0, and 20.0 kGy. Principal component analysis indicated that volatile constituents from samples irradiated at 15.0 and 20.0 kGy showed a chromatographic profile more similar to nonirradiated sample than samples exposed to other applied doses [40]. The content of 4-acetyltoluene, geranial, and *δ*-dodecalactone was not observed only at a dose of 5.0 kGy. Compounds 2-acetylpyrrole and capric acid were identified at 5.0 kGy. (*E*,*E*)-2,4-heptadienal was not observed only at 15.0 kGy. *β*-ciclocitral; 1,1,6-trimethyl-1,2-dihydronaphthalene; and eugenol were not observed only at 20 kGy. Benzaldehyde; durol; 2,4-nonadienal; (*E*,*E*)-2,4-decadienal; isopiperitenone; and benzyl benzoate were only identified at a dose of 10 kGy. Linalool, safranal, *α*-ocimene, and (*E*)-2-decenal were only identified at a dose of 15.0 kGy. Guaiacol, 4-ethylphenol, 4-isopropylbenzaldehyde, and isopropyl methoxy pyrazine were only identified at 20.0 kGy. The content of safranal did not change at doses higher than 15.0 kGy [40].

Bud-unfermented samples of *C. sinensis* were exposed at doses of 5.0, 10.0, 15.0, and 20.0 kGy. Irradiated samples exhibited 82 compounds unidentified in the nonirradiated sample. Benzaldehyde, phenylmethanol, phenylacetaldehyde, geranial, 4-vinylguaiacol,

spathulenol, phytone, farnesyl acetone, and phytol were only observed at a dose of 5.0 kGy. Compounds 1-tetradecanal, *cis*-geraniol, octadecanal, and *cis*-linalool oxide were not observed only at a dose of 5.0 kGy. Hexanoic acid, acetophenone, *p*-toluol, (*E*)-2-nonenal, 4-decalactone, *β*-damascenona, 2,6-dimethyl naphthalene, *β*-ionone, (+)-aromadendrene, farnesol, and benzyl benzoate were only identified in the sample irradiated at a dose of 10.0 kGy. Compound 4-vinylguaiacol was not observed only at a dose of 10.0 kGy. (+)-Aromadendrene, 2,6-dimethyl-naphthalene, 4-decalactone, and *p*-toluol were not observed only at a dose of 15.0 kGy. Butanoic acid and *trans*-2-decenal were only identified at a dose of 20.0 kGy. Benzyl benzoate and caryophyllene oxide were not observed only at a dose of 20.0 kGy [41].

9. Essential oils from overall herbs

Samples of *Rosmarinus officinalis* L. (rosemary) obtained from a local market in Ankara (Turkey) were exposed at doses of 7.0, 12.0, and 17.0 kGy. EO yield was not affected when samples were exposed to *γ*-radiation. The content of butylbenzene decreased in irradiated samples (average values considering all irradiated materials = 0.6%) in relation to the nonirradiated sample (0.78%). The content of *α*-terpinene decreased for the irradiated samples at doses of 12.0 and 17.0 kGy (average values considering all the irradiated materials = 0.3%) in relation to nonirradiated sample (0.37%), but was not changed at 7.0 kGy. The content of limonene, geraniol, and carvacrol decreased for a sample irradiated at 17.0 kGy (2.47, 1.13, and 0.24%, respectively) in relation to nonirradiated sample (2.98, 1.85, and 0.62%, respectively). The content of limonene, geraniol, and carvacrol was not changed for irradiated samples at other doses of radiation. Cumin aldehyde was only identified in irradiated samples (average values considering all irradiated materials = 0.7%). The content of 1,8-cineole increased in irradiated sample at 17.0 kGy (38.2%) in relation to nonirradiated sample (30.73%), but was not changed at other radiation doses. The content of *α*-pinene, camphene, *β*-pinene, myrcene, *α*-phellandrene, *δ*-3-carene, p-cymene, *γ*-terpinene, 3-pinanone, bornelo, terpinen-4-ol, *α*-terpineol, verbenone, thymol, and *β*-caryophyllene was not affected when the samples were exposed to *γ*-radiation [24].

Samples of *R. officinalis, Nasturtium officinale* (watercress), and *Cynara scolymus* (artichoke) were exposed at doses of 10.0, 20.0, and 30.0 kGy. Absorption spectrum of irradiated EO did not exhibit significant differences in relation to nonirradiated EO [19].

Samples of *Trifolium pratense* L. (clove) purchased from a local market in Mumbai (India) were exposed to *γ*-radiation at a dose of 10.0 kGy. Extraction yield of EO increased for the irradiated sample (18.88%) in relation to nonirradiated sample (15.25%). The content of benzylalcohol, eugenol, *β*-caryophyllene, humulene, eugenol acetate, and vanillin did not change for the irradiated sample [42].

Samples of *Elettaria cardamomum* (cardamom) purchased from a local market in Mumbai (India) were exposed to a dose of 10.0 kGy. The overall yield of EO was not changed for irradiated and nonirradiated samples (5.80 and 5.78%, respectively). The higher content of

α-pinene, sabinene, myrcene, limonene, and nerolidol was observed in irradiated samples (0.68, 1.78, 1.48, 1.23, and 1.89%, respectively) in relation to nonirradiated sample (0.36, 1.40, 1.20, 0.94, and 1.20%, respectively). The content of α-terpineol in irradiated samples (45.43%) decreased in relation to nonirradiated sample (49.0%)[42].

Samples of *Myristica fragrans* (nutmeg) purchased from a local market in Mumbai (India) were exposed to a dose of 10.0 kGy. EO extraction yield was similar to nonirradiated and radiated samples (3.12 and 3.47%, respectively). The content of α-terpeniol, 1-terpinene-4-ol, and myristicin in irradiated samples (6.64, 17.67, and 31.72%, respectively) increased in relation to nonirradiated sample (1.0, 8.6, and 5.0%, respectively). The content of sabinene, β-pinene, and elemicin decreased in comparison to nonirradiated sample [42].

Aerial parts of *Zataria multiflora* purchased from a local market in Shiraz (Iran) were submitted to γ-radiation at 10.0 and 25.0 kGy. EO extraction yield was similar to irradiated and nonirradiated samples (4.0% for each sample). The content of thymol and carvacrol in a nonirradiated sample (61.8 and 10.5%, respectively) decreased for irradiated samples at 10.0 kGy (49.3 and 6.6%, respectively) and 25.0 kGy (45.3 and 6.3%, respectively). On the other hand, the content of *p*-cymene and γ-terpinene in a nonirradiated sample (7.5 and 4.4%, respectively) increased for irradiated samples at 10.0 kGy (16.2 and 8.6%, respectively) and 25.0 kGy (17.5 and 9.3%, respectively) [43].

Leaves and flowers of *T. vulgaris* from Morocco were exposed to γ-radiation at 10.0, 20.0, and 30.0 kGy. Carvacrol was the main component, exhibiting an increase of concentration dose dependent with γ-radiation (81.29% for a nonirradiated sample and 84.0% for an irradiated sample at 30.0 kGy). The content of α-pinene was not altered for the irradiated samples. The content of α-thujene and γ-terpinene decreased at 30 kGy of radiation (0.55 and 2.49%, respectively) in relation to the nonirradiated sample (0.82 and 2.77%, respectively). On the other hand, the content of *O*-acetylthymol increased at 30.0 kGy (0.41%) in relation to nonirradiated sample (0.28%). The content of δ-terpinene increased at 20.0 kGy (0.86%) in relation to the nonirradiated sample (0.75%). The content of *p*-cymene increased at 10.0 and 20.0 kGy (average values considering all irradiated materials = 4.6%) in relation to the nonirradiated sample (3.9%). The content of β-humulene increased at 20.0 and 30.0 kGy (average values considering all irradiated materials = 3.21%) in relation to the nonirradiated sample (2.07%) [44].

Leaves and flowers of *Mentha pulegium* collected in Boujdour (Morocco) were submitted to γ-radiation at 10.0, 20.0, and 30.0 kGy. The content of 3-octanol, *p*-mentha-3,8-diene, menthone, isomenthol, and piperitenone increased for irradiated samples (average values considering all irradiated materials = 0.3, 0.2, 2.1, 0.7, and 8.1%, respectively) in relation to the nonirradiated sample (0.23, 0.10, 1.37, 0.43, and 6.54%, respectively). On the other hand, the content of limonene and piperitone oxide decreased for irradiated samples (average values considering all irradiated materials = 1.4 and 0.7%, respectively) in relation to nonirradiated samples (1.59 and 1.82%, respectively). The content of α-pinene increased at 10.0 kGy (0.42%) in relation to nonirradiated sample (0.37%). The content of β-humulene increased at 10.0 kGy (0.37%) and decreased at 20.0 and 30.0 kGy (average values considering all irradiated materials = 0.13%) in relation to nonirradiated sample (0.25%) [44].

10. Terpenes from essential oils

Geraniol and nerol purchased from Fluka (code. 72170) were solubilized with methanol (100 mg/mL) and were exposed to γ-radiation at a dose of 5.1 Gy/min. Nerol was stable until 96 h of exposition to radiation. On the other hand, irradiated geraniol exhibited changes on the GC/MS profile in relation to the nonirradiated geraniol. Geraniol was isomerized in nerol and linalool. The content of linalool increased with radiation time, from 0.0 (at 24 h) to 8.4% (at 120 h). The content of nerol also increased with radiation time, from 0.0 (at 24 h) to 57.0% (at 120 h) [45].

Citronellol purchased from Aromáticos Gama (Mexico) was exposed to 1.45, 6.07, and 10.02 kGy. The content of citronellol decreased in irradiated samples (95.09, 94.77, and 86.95%, respectively) in relation to nonirradiated sample (97.52%). The content of rhodinol (an impurity) decreased in irradiated samples (0.75, 0.76, and 0.85%, respectively) in relation to nonirradiated sample (2.34%). On the other hand, the content of dihydrocitronellol (another impurity) increased in irradiated samples (1.61, 1.75, and 1.75%, respectively) in relation to nonirradiated sample (0.14%). Moreover, the content of citronellal and hydroxycitronellal increased in irradiated samples (average values considering all irradiated materials = 1.3 and 3.4%, respectively) in relation to nonirradiated sample (0.50 and 3.36%, respectively) [46].

Pure standards of α-pinene, phellandrene, *p*-cymene, eucalyptol, limonene, linalool, lavandulol, terpin-4-ol, and linalyl acetate purchased from Fluka were exposed to 25.0 kGy. The content of these compounds did not change when the samples were exposed to radiation [16].

Pure standards of (+)-camphor, 1,8-cineol, *trans*-cinnamaldehyde, eugenol, ethyl hexanoate, α-ionone, (*S*)-(−)-limonene, 2-phenethyl alcohol, and α-terpineol purchased from Aldrich (code. T3407), (±)-linalool purchased from Fluka (code. 51782), and vanillin purchased from Merck (code. 121-33-5) were exposed to 10.0 and 50.0 kGy. The contents of (±)-linalool, α-terpineol, and α-ionone in an irradiated sample (average values considering all irradiated materials = 0.9, 0.9, and 1.3%, respectively) slightly decreased in relation to nonirradiated sample (1.00, 0.97, and 1.40%, respectively). The content of (S)-(−)-limonene in an irradiated sample at 50.0 kGy (1.24%) decreased in relation to nonirradiated sample (1.30%). No significant differences were verified for the contents of (+)-camphor, 1,8-cineol, *trans*-cinnamaldehyde, eugenol, ethyl hexanoate, and (*S*)-(−)-limonene when exposed to radiation at 10 kGy. Moreover, no significant differences were also verified for the contents of 2-phenethyl alcohol and vanillin for irradiated and nonirradiated samples [47].

11. Discussion

Internal and external factors can determine yield and composition of EOs from plant materials. Internal factors are usually genetic, physiological, and evolutionary (stage of maturity). On the other hand, external factors are usually seasonality, circadian rhythm, temperature, water availability, nutrient availability, air pollution, altitude, mechanical stimuli, attack pathogens, or extraction conditions [13].

The effects of gamma radiation on EOs constituents also depend on the different factors, such as radiation dose, dose rate, vegetal species, temperature, and sample state. Exposition to γ-radiation may increase or decrease the extraction yield of EO and the content of their constituents [35].

The higher yield of EO extraction verified for the irradiated samples has been usually attributed to radiation-induced disruption of the cell wall structure, providing a higher extractability of oil from the plant tissues. Moreover, changes on EO extraction yield can be due to a recombination of the radiolytic products with time. Specific effects can be observed on a secondary metabolite in different essential oils even though submitted to the same radiation conditions. The content of a constituent upon radiation is presumably due to its radiation sensitivity at different doses [14].

Detection and identification of radiolytic products are very important in the study of the effect of radiation in plant materials because changes in the chemical structure of some compounds may lead to formation of toxic radical species. However, the identification of these structures on essential oils is not easy. Radiolytic products are in trace amounts and usually undetected by GC/MS or coelute with other oil constituents. Studies of the effect of γ-radiation on pure compounds are useful to understand these degradation processes, but the response of these compounds could be different when they are a part of a vegetal material.

Volatile compounds, such as terpenes and terpene derivatives, are usually majoritary components in EOs from plant material and contain different chemical functional groups. A volatile compound in different EOs is under specific reactional environments and the conditions of each EO submitted to different ways of isomerization, oxidation, and hydroxylation when exposed to γ-radiation provide new compounds [24].

The effects of radiation on the volatile compounds are different when a constituent is contained in different vegetal specie. For example, the monoterpene linalool showed a great sensitivity to γ-radiation in leaf EO from *O. basilicum* [20]. However, this compound was radiation-resistant in leaf EO from *T. vulgaris* [16]. In the same context, the content of carvacrol significantly decreased in aerial part EO from *Z. multiflora* [43] and increased at doses up to 5.0 kGy in the leaf EO from *O. vulgare*, whereas it was not affected by γ-radiation in leaf EO from *T. vulgaris* [16].

Moreover, the content of α-pinene significantly decreased in the EO from *A. gigas* Nakai [3]. However, the content of this volatile compound increased after exposition to γ-radiation in the aerial part EO from *Z. multiflora* [16]. Another example is the menthone, which increased according to the γ-radiation dose increase in the EO from *M. piperita* [17], but its content increased after γ-radiation at 10.0 kGy in the EO from *M. pulegium* and decreased at 20.0 and 30.0 kGy [44].

In spite of the exposition to radiation on secondary metabolites studied a long time ago, new studies are necessary to better understand its effect on cell structure and chemical structure of the constituents of the EOs from vegetal material. In addition, it seems to be interesting to study whether a modification of the structure of some pure compounds (even in trace) could lead to the formation of toxic, long-lived radicals [16].

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