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ORIGINAL PAPER

Investigation of the effect of the drying techniques on the volatile constituents' profiles of sow thistle (*Sonchus oleraceus* L.) using headspace solid-phase microextraction with comprehensive two-dimensional gas chromatography–time of flight mass spectrometry (HS-SPME–GC × GC–ToFMS)

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Abstract

Sonchus oleraceus L. is a leafy vegetable commonly consumed in traditional Mediterranean diets as a wild edible plant for its nutritional, sensory, and health benefits. This study aimed to track changes in the volatile constituents of *S. oleraceus* after oven and microwave drying in correlation with the plant's proximate analysis, amino acid profile, sugar content, and fatty acid analysis to predict the main pathways of volatile generation during thermal processing. Comprehensive two-dimensional gas chromatography time-of-flight mass spectrometry was used for the volatile analysis. A total of 247 compounds belonging to 13 different classes were identified. Alcohols, terpenes, and esters were the most abundant groups in the fresh sample. Levels of the products of thermal oxidation of fatty acids, such as aldehydes and ketones, increased dramatically at the expense of alcohols and terpenes. Additionally, the number of N- and O-heterocycles formed through the Maillard reaction increased, corresponding to the reduction of amino acids and sugars. After drying, sulfur-containing compounds were generated as products and intermediates of methionine Strecker degradation. Oven-dried plant displayed the highest contents of ash (19.86%), protein (26.21%), and fat (3.89%), following moisture reduction to 3.82%. A downward trend in the amino acid profile was noted during drying, particularly in oven-dried plants, including arginine, tyrosine, valine, cysteine, isoleucine, and phenylalanine. Microwave-dried plant retained higher levels of these amino acids compared to oven-dried ones. The sugar content varied based on the drying method; the oven-dried plant had lower levels of sucrose, glucose, and fructose than the microwave-dried plant. Based on Gas Chromatography analysis, palmitic, stearic, and linolenic acids were predominant in fresh and dried samples. This study clarifies the metabolic changes that occur during drying, which are crucial for ensuring safety and shelf life.

Keywords *Sonchus oleraceus* L. · Oven-drying · Microwave-drying · Volatiles · GC ×GC-ToFMS proximate analysis

Introduction

Wild edible plants are appreciated for their seasonal traits, sensory qualities, and beneficial phytochemicals [1]. In the Mediterranean, they enhance local cuisine with its flavors and aromas. Wild plants can also serve as sustainable crops, offering new flavors and being nutrient-rich. Local traditions dictate their usage, whether eaten raw or cooked, alone or with other species [2]. *Sonchus oleraceus* is a wild edible plant that belongs to the *Asteraceae* family, also known as milkweed or milkweed-smooth. It is often found in agricultural regions where it grows as a weed crop. The

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plant is native to Europe, North Africa, and West Asia but has spread to other parts of the world, including North and South America, India, China, and southern Australia [3]. *S. oleraceus* is a plant that is known to contain a wide range of phytochemical compounds, including sesquiterpene lactones, flavonoids, flavanols, proanthocyanins, total phenols, saponins, phytate, and alkaloids [4]. According to Li and Yang [5], it contains fatty acids, vitamin C, carotenoids, oxalic acid, and minerals, making it a nutritious supplement. Overall, Sonchus is an excellent source of various phytochemicals and nutrients that can have several health benefits, including antioxidant, antifungal, anti-toxigenic, antidiabetic, antibacterial, anti-inflammatory, and antitumor properties [5, 6]. It is also used as a remedy for headaches, general pain, rheumatism, and as a general tonic, anxiolytic, antinociceptive, and anti-aging agent. The extract also exhibits hepatoprotective activity and is helpful in cardiovascular therapy [7, 8].

Despite its extensive use in cooking, there is still a need for more information on the volatile and aroma compounds of *S. oleraceus* that contribute to the overall sensory experience of food. Recently, there has been a growing interest in identifying volatile compounds in *S. oleraceus* due to their bioactivities, which remain effective when consumed fresh, and their organoleptic characteristics [9]. However, only Fukalova [9] fully described these characteristics and analyzed the volatile profiles of *S. oleraceus* cultivated in Valencia province (Spain) using head-space solid-phase microextraction (SPME) coupled with gas chromatography and mass spectrometry (GC-MS).

SPME is a fast and easy-to-automate technique used to analyze volatiles. Combined with comprehensive two-dimensional gas chromatography–time of flight mass spectrometry (GC×GC-ToFMS) to identify volatile compounds, as it offers an unrivaled peak capacity and spatial separation of peaks, allowing for better deconvolution and identification of compounds, overcoming the limitations of single dimension GC, like restricted selectivity and lower peak capacity [10, 11]. However, the applications of the combined techniques for monitoring plant volatiles are still limited, and no work has been reported concerning the study of the volatiles of *S. oleraceus*.

Drying is a crucial process for plant storage, as it reduces water content and prevents metabolic activity in the plant's body. It also aids in marketing medicinal plants by reducing their weight and volume. The temperature during drying is pivotal for preserving the active ingredients of essential oils, which accumulate in tissue cells and can impact the volatile constituents of medicinal and aromatic plants [9]. However, our research stands out as it is the first to report on *S. oleraceus*.

Consequently, and based on the information above, the current study aimed to evaluate and compare the volatile compounds profiles of fresh, oven dried, and microwave dried *S. oleraceus* plant cultivated in Egypt for the first time in our knowledge using HS-SPME–GC × GC–ToFMS. In addition, proximate analysis, along with the amino acid profile and sugars, which are compounds involved in thermally generated flavor formation, was also tracked during drying to interpret the eventual changes in the volatile profile. Identifying the volatile compounds in *S. oleraceus* can promote traditional gastronomy and provide a better understanding of its flavor. It can also guide the commercial exploitation of wild edible plants as alternative food sources and aid in making informed decisions on quality parameters.

Materials and methods

Plant materials

The aerial parts of *Sonchus oleraceus* L. were collected from El-Qalag, El-Qaliobia, Egypt, in November 2022; a taxonomist identified the *S. oleraceus* at the Department of Medicinal and Aromatic Plants Research, National Research Center (Cairo, Egypt). Plant samples were put in air-sealed plastic food bags, stored at deep freezing conditions (-80 °C), prior to further analyses. Diethyl ether and methanol were purchased from Fisher Chemicals (Pittsburgh, USA). The standards with ≥97% purity and n-alkanes C_6–C_{20} mixture were obtained from Sigma Aldrich Chemical Co. (St. Louis, MO, USA).

Drying of Sonchus oleraceus plant

One hundred grams of *S. oleraceus* aerial parts were subjected to microwave heating for 3 min at 80 °C with 1400 W input power (Daewoo DE Microwave, Model: KoG-181G, 200–240 V 50 Hz, Korea). Another 100 g was dried in a conventional electric oven (Electra Electronic Ltd., Model: EK-450-OT, Shenzhen, China) at 60 °C for 25 min. The drying parameters were chosen based on Ou et al. [12]. The treated samples were ground in a grinder and stored until analysis. The analyses were run in triplicate. The moisture content of the microwave-dried sample was 3.82%, whereas the oven-dried sample was 9.87% compared to the fresh, control sample (90.44%), as shown in Table 1.

Volatile analysis using HS-SPME-GC x GC ToFMS

Volatiles were separated and analyzed using the previously described method [10]. The extraction of volatiles was conducted using SPME with an 85-µm Carboxen™/

Table 1 Proximate composition, amino acids, sugars, and fatty acids of *fresh and dried S. oleraceus* plants (on a dry-weight basis)

Component	Mean values of approximate analysis (% on dry-weight basis)		
	Fresh plants	Oven dried plants	Microwave dried plants
Dry mass	9.56 ± 0.16^{c}	96.18 ± 0.08^{a}	90.13 ± 0.08^{b}
Moisture	90.44 ± 0.15^{a}	3.82 ± 0.08^{c}	9.87 ± 0.08^{b}
Ash	18.52 ± 0.01^{a}	19.86 ± 0.81^{a}	18.39 ± 0.08^{a}
Protein	25.57 ± 0.04^{b}	26.21 ± 0.32^{a}	25.65 ± 0.08^{ab}
Fat	3.71 ± 0.01^{b}	3.89 ± 0.04^{a}	3.73 ± 0.08^{ab}
Crude fiber	8.05 ± 0.13^{a}	7.66 ± 0.17^{ab}	7.43 ± 0.08^{b}
Total carbohydrates	44.16 ± 0.16^{a}	42.39 ± 0.70^{b}	44.81 ± 0.33^{a}
Amino acids (mg/g protein)			
Aspartic acid	46.80 ± 0.62 ^{b}	53.37 ± 4.08 ^{a}	46.95 ± 2.52 ^{b}
Glutamic acid	64.05 ± 0.92 ^{b}	76.76 ± 1.49 ^{a}	77.51 ± 1.81 ^{a}
Serine	79.25 ± 0.03 ^{b}	81.15 ± 1.43 ^{ab}	83.04 ± 1.63 ^{a}
Glycine	37.87 ± 0.23 ^{b}	40.89 ± 2.18 ^{ab}	43.39 ± 2.14 ^{a}
Histidine	57.04 ± 0.43 ^{a}	59.58 ± 9.06 ^{a}	45.66 ± 5.07 ^{a}
Arginine	59.91 ± 0.27 ^{a}	56.99 ± 3.65 ^{a}	58.03 ± 3.34 ^{a}
Threonine	87.27 ± 0.31 ^{a}	87.49 ± 5.47 ^{a}	82.95 ± 4.74 ^{a}
Alanine	50.55 ± 0.82 ^{a}	50.19 ± 1.21 ^{a}	48.41 ± 1.00 ^{a}
Proline	30.52 ± 0.09 ^{c}	44.57 ± 0.85 ^{a}	38.54 ± 0.48 ^{b}
Tyrosine	88.50 ± 0.56 ^{a}	56.96 ± 4.78 ^{b}	63.46 ± 6.31 ^{b}
Valine	40.30 ± 0.33 ^{a}	37.76 ± 1.46 ^{a}	38.69 ± 1.63 ^{a}
Methionine	46.55 ± 0.42 ^{c}	60.48 ± 0.04 ^{a}	51.83 ± 0.05 ^{b}
Cysteine	19.12 ± 0.10 ^{a}	11.79 ± 0.86 ^{b}	13.46 ± 1.18 ^{b}
Isoleucine	79.08 ± 0.35 ^{b}	75.62 ± 0.79 ^{c}	82.91 ± 1.05 ^{a}
Leucine	48.27 ± 0.60 ^{a}	49.45 ± 7.44 ^{a}	50.90 ± 7.05 ^{a}
Phenylalanine	55.78 ± 0.33 ^{ab}	48.31 ± 2.66 ^{b}	59.01 ± 3.41 ^{a}
Lysine	58.33 ± 0.29 ^{a}	61.95 ± 4.24 ^{a}	64.69 ± 4.11 ^{a}
Sugar (mg/100 g sample)			
Sucrose	5.54 ± 0.07^{c}	317.68 ± 1.36 ^{b}	966.84 ± 5.07 ^{a}
Glucose	545.18 ± 1.14 ^{b}	389.63 ± 2.12 ^{c}	725.26 ± 3.53 ^{a}
Fructose	170.50 ± 1.12 ^{b}	76.78 ± 0.67 ^{c}	247.96 ± 2.82 ^{a}
Total sugars	721.22 ^{c}	784.09 ^{b}	1940.06 ^{a}
Fatty Acids Composition (%)			
Palmitic acid	34.93 ± 1.12 ^{a}	14.89 ± 0.41 ^{c}	26.15 ± 1.01 ^{b}
Palmitoleic acid	0.85 ± 0.03 ^{b}	1.36 ± 0.06 ^{a}	0.62 ± 0.01 ^{c}
Stearic acid	16.49 ± 0.21 ^{a}	7.04 ± 0.09 ^{c}	13.10 ± 0.88 ^{b}
Oleic acid	2.42 ± 0.01 ^{a}	0.91 ± 0.01 ^{c}	2.02 ± 0.06 ^{b}
Linoleic acid	4.90 ± 0.02 ^{c}	7.53 ± 0.06 ^{a}	5.37 ± 0.09 ^{b}
Linolenic acid	22.07 ± 0.98 ^{c}	59.25 ± 1.44 ^{a}	38.63 ± 1.21 ^{b}
Arachidic acid	2.14 ± 0.05 ^{a}	0.91 ± 0.01 ^{c}	1.10 ± 0.02 ^{b}
Heneicosanoic acid	0.80 ± 0.01 ^{c}	0.94 ± 0.02 ^{b}	1.23 ± 0.04 ^{a}
Behenic acid	5.13 ± 0.10 ^{a}	2.35 ± 0.08 ^{c}	3.60 ± 0.07 ^{b}
Erucic acid	8.95 ± 0.30 ^{a}	3.63 ± 0.11 ^{c}	6.98 ± 0.13 ^{b}
Lignoceric acid	1.32 ± 0.04 ^{a}	1.2 ± 0.02 ^{b}	1.20 ± 0.04 ^{ab}

Data are presented as means ± standard error (M ± SE). Rows with different superscripts reveal significant differences ($p < 0.05$)

polydimethylsiloxane (CAR/PDMS) (StableFlex) fiber purchased from Supelco (Bellefonte, PA, USA). Two grams of each *S. oleraceus* sample was placed in 20-mL headspace vials, equilibrated for 6 min at 58 °C, and then extracted for 38 min. Volatiles were analyzed by GC×GCToFMS using an Agilent 6890 N gas chromatograph (Agilent Technologies, Palo Alto, CA, USA) equipped with a secondary oven and cryogenic (N_2) modulator coupled to a PEGASUS 4D time-of-flight mass spectrometer (LECO, St. Joseph, MI). Separation was performed on an SLB-5 (30 m × ⌀ 250 µm, df 0.25 µm; Supelco, Bellefonte, PA) as a first-dimension column and an SPB-50 (0.8 m × ⌀ 250 µm, df 0.25 µm; Supelco, Bellefonte, PA) as the second-dimension column.

The ToFMS operated in a mass range of m/z 33–383 and a detector voltage of 1700 V at 150 spectra/s. The data were collected and processed using a LECO ChromaTOF v.4.40 (LECO, St. Joseph, MI). The deconvoluted mass spectra of registered compounds were searched against the NIST library (version 2.0) of mass spectra. The analyte match criteria utilized the following parameters: signal-to-noise (S/N) ratio of 50 and a minimum spectral similarity match of 700. The peak areas of modulated peaks of the same unique mass were summarised for each annotated compound. Linear retention indices (LRI) were calculated relative to a series of alkanes (C_6–C_{20}) on the first-dimension column (DB-5 type). The peaks were tentatively identified based on the mass spectral library match and the comparison of LRI with that provided in the NIST database. Compounds in fewer than 50% of samples were eliminated from statistical procedures.

Proximate analysis, amino acid profile, sugar content, and fatty acid composition

The fresh and dried *S. oleraceus* plants underwent analysis for moisture, crude protein, fat, ash, and crude fiber using the AOAC method [13]. Other total carbohydrates were then calculated using the difference. Waters 600E HPLC system (Waters Corp., Milford, MA, USA) measured the amino acid profile using the Pico-Tag method described by Razal et al. [14]. Sugar analysis was performed using an Agilent 1100 series liquid chromatography system with an autosampler and refractive index detector (RID). The Shimpack SCR-101 N column was used with ultrapure water as the mobile phase, at a flow rate of 0.7 mL/min and a total run time of 20 min, employing isocratic elution. Carbohydrate concentrations were determined by integrating areas and comparing them to standard curves of glucose, fructose, and sucrose (Sigma-Aldrich, St. Louis, MO, USA).

Fatty acid methyl esters are produced using an acidic catalyst that facilitates the reaction between fats and methanol in the presence of a 7% boron trifluoride-methanol solution, along with butylated hydroxytoluene (BHT) as an

antioxidant. This process occurs at 100 °C for 45 min, and the resulting product is then injected into hexane. The analysis was performed using a gas chromatograph model 7890B from Agilent (Folsom, CA, USA). Separation of the compounds was achieved on a Zebron ZB-FAME column (60 m × 0.25 mm internal diameter × 0.25 µm film thickness). The analyses utilized hydrogen as the carrier gas, with a flow rate of 1.8 ml/min in a split mode of 1:50. The injection volume was 1 µl, and the temperature program commenced at 100 °C for 3 min, followed by a temperature increase of 2.5 °C per minute until reaching 240 °C, which was held for an additional 10 min. The injector and flame ionization detector (FID) were maintained at temperatures of 250 °C and 285 °C, respectively.

Statistical analysis

All results were expressed as mean values ± standard error, using a one-way analysis of variance (ANOVA) followed by the Duncan test, conducted with the SPSS statistical software.

Results

Volatile analysis using HS-SPME-GC x GC ToFMS

In total, 247 volatile components were detected and tentatively identified in the fresh and dried *S. oleraceus* plants, including 36 alcohols, 31 aldehydes, 13 aliphatic hydrocarbons, 14 aromatic hydrocarbon, 1 acid, 24 esters, 1 ether, 25 O-heterocyclic compounds, 25 N-heterocyclic compounds, 29 ketones, 4 N-containing compounds, 4 phenols, 5 S-containing compounds, and 35 terpenes (Table 1). GC×GC chromatograms of volatiles in the analyzed dried plant are presented in Fig. 1. The abundance distribution between the chemical classes is given in Fig. 2. The most abundant chemical class in the fresh plant comprised alcohols, with 38% compared to the other identified volatiles, followed by terpenes (22%), esters (14%), aldehydes (9%), and ketones (4%) as shown in Fig. 2A. In oven-dried plant (Fig. 2B), the aldehydes (29%) were dominant; however, the second dominant class was esters (16%), followed by terpenes (12%), alcohols (9%), and N-heterocycles (9%). Aldehydes (30%) were the dominant compounds in the microwaved plant, followed by esters (19%), alcohols (14%), terpenes (8%), and N-heterocyclic compounds (7%), as illustrated in Fig. 2C. The abundance of the volatile classes, especially aldehydes, esters, aliphatic and aromatic hydrocarbons, N-heterocycles, furans, and ketones, increased gradually from fresh to roasting using the microwave at the expense of both alcohols and terpenes (Fig. S1).

In line with the higher content of alcohols in the fresh plant, 28 compounds were identified compared to 18 compounds in the oven-dried plant and 12 compounds in the microwaved plant. 2-methyl-1-butanol represents the major alcohol in the fresh plant, with 20% of the class. Meanwhile, 1-ethoxy-1-propanol and 3-buten-1-ol represent the predominant components, with 31% and 41% of the alcohol class in the oven-dried and microwaved plant, respectively (Fig. S1). 2-methyl-butanal represents the main aldehyde in all dried samples, but with different percentages among the aldehyde class members: 25% in fresh plant, 33% in oven-dried plant, and 28% in microwaved plant. More aldehydes were detected in both oven-dried and microwaved plants (27 and 17 compounds) compared to the fresh plant (15 aldehydes), which agreed with the increase of this class among the total identified volatiles upon drying.

Ethyl acetate dominates fresh and dried *S. oleraceus* plants despite the quantitative differences in the ester class compared to the other volatile groups (Fig. S1). Both β-pinene and limonene represent the major terpenes in all analyzed samples, in addition to linalool (14% of the total terpenes) found in the microwaved plant. In addition to tetrahydrofuran (32% of the class), which is the major O-heterocyclic compound in fresh plant, other constituents like butyrolactone (34%), and 2-furan carboxaldehyde, 5-methyl- (5-HMF) (14%) found as a major constituent in both oven-dried and microwaved plants with more members of this class. The N-heterocyclic class showed a dramatic increase over-drying, from only one compound in the fresh plant (methyl pyrazine) to 19 and 20 compounds in both oven-dried and microwaved plants, with many dominants like 2-acetyl pyrrole, 2,5- and 2,6-dimethyl pyrazine (Table S1 and Fig. S1).

Proximate analysis of fresh and dried Sonchus oleraceus L. plant

Table 1 shows the proximate composition of *S. oleraceus* plant samples, encompassing fresh, oven-dried, and microwave-dried variants. The findings show that all metrics saw substantial alterations ($p < 0.05$) when the plants were subjected to heat treatment. The initial moisture content of the fresh plant was 90.44% (wet basis). The drying temperature had a direct influence on the reduction in moisture content of the plant. The moisture content was reduced, declining to 3.82% and 9.87% in oven- and microwave-dried plants, respectively.

The crude protein concentration of the fresh plant was 25.57% (on a dry-weight basis). The crude protein content of the dried samples significantly increased ($p < 0.05$) to 26.205 and 25.645% in dried samples (Table 1). Regarding fat content, the fresh plant contained 3.71%, but this figure

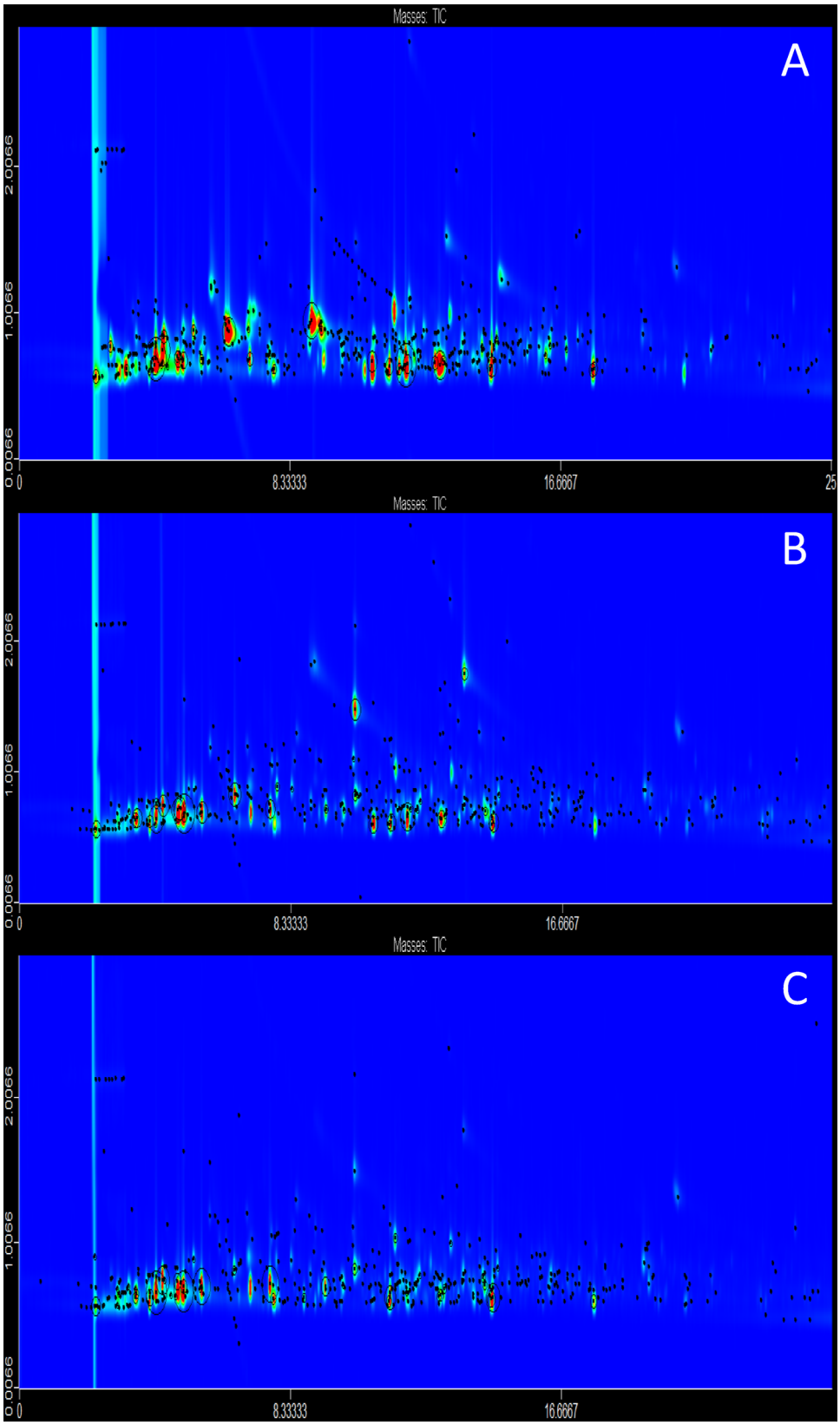


Fig. 1 GC× GC-ToFMS chromatograms of volatiles extracted from (A) fresh, (B) oven-dried, (C) microwaved *S. oleraceus* plants

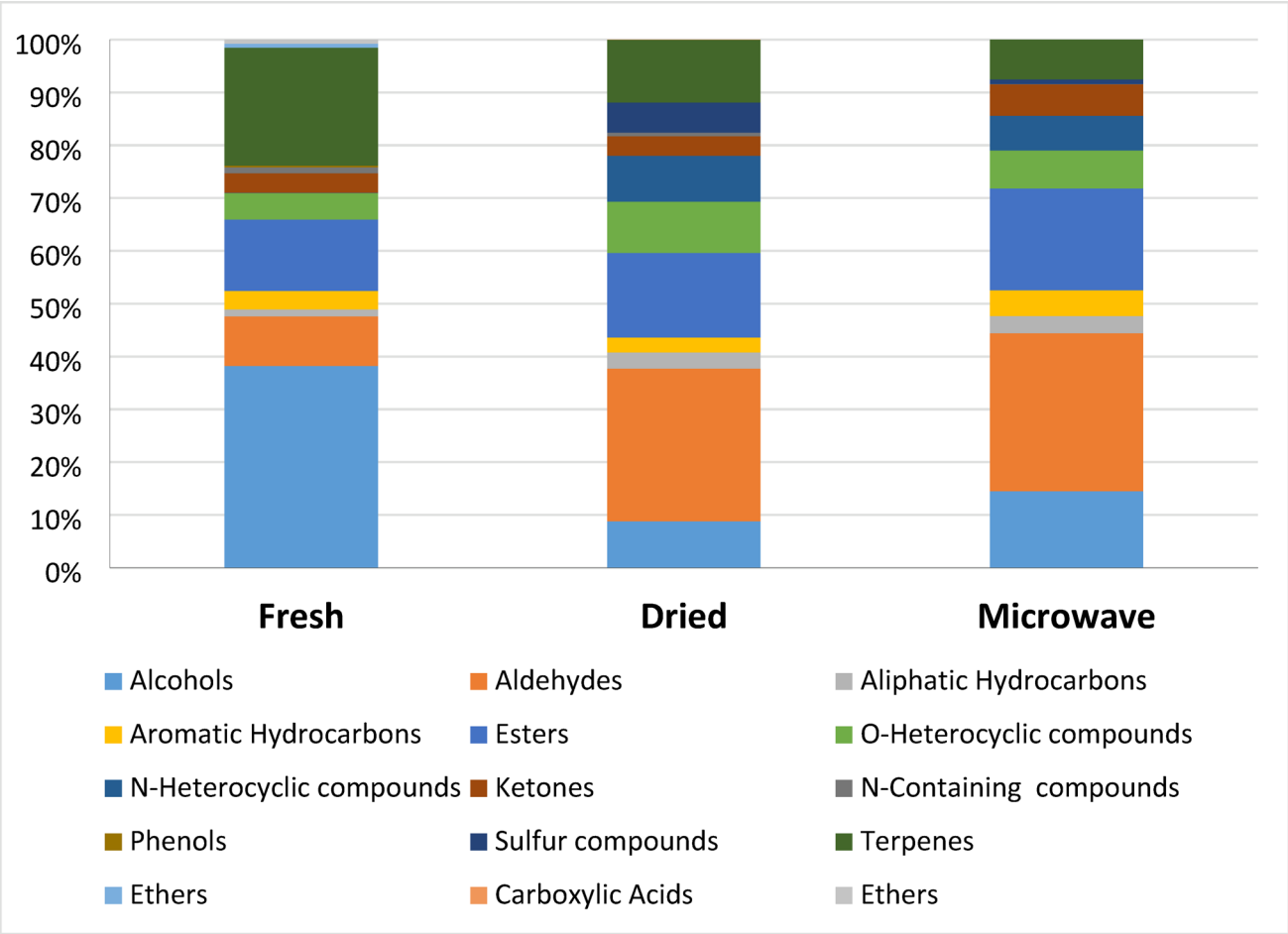


Fig. 2 The percentage contribution of the chemical classes to the overall identified volatiles of the (**A**) fresh, (**B**) oven-dried, and (**C**) microwaved *S. oleraceus* L. plants

increased significantly, with the oven-dried sample having the highest value (3.89%), and the microwaved sample having 3.73%.

The crude fiber content of the dried plant decreased proportionally with the rising temperature, based on the drying technique used. The fresh plant showed the highest fiber concentration (8.05%), while the drying techniques led to significant differences, with 7.66% and 7.425% for the dried samples (Table 1). Again, the content of carbohydrates was found to be dependent on the method used for drying. The content was the highest for a microwave-dried sample (44.81%) and the lowest for oven-dried ones (42.385%). Table 1 also shows the ash content in fresh and dried plants. The ash content in fresh samples was lower (18.515%) than that of oven-dried plant (19.86%), but higher than that of microwaved plant (18.39%). The ash content, however, did not differ significantly among the three samples ($P < 0.05$).

Drying of plants decreased many amino acids, irrespective of the applied technique. A significant downward trend was observed for many essential and non-essential amino acids upon oven-drying, compared to fresh plants, especially in oven-drying plants such as tyrosine, cysteine, isoleucine, and phenylalanine (Table 1). The same trend was observed for the microwave-dried plants, but only for tyrosine and cysteine. In contrast, a significant increase in aspartic acid, glutamic acid, serine, glycine, proline, and methionine was observed in the oven-dried plant compared to the fresh one. The remaining essential and non-essential amino acids, like histidine, arginine, threonine, alanine, valine, leucine, and lysine, showed non-significant differences between fresh and dried samples. The microwave-dried sample showed higher contents of serine, glycine, isoleucine, and phenylalanine compared to the oven-dried sample. The highest amounts were 88.50 and 87.27 mg/g protein for tyrosine and threonine in fresh plants, while threonine and serine were the highest in oven-dried plants with 87.49 and 81.15 mg/g protein, and in microwave-dried plants with 82.95 and 83.04 mg/g protein.

Again, the sugar content depended on the drying method, where the oven-dried plants showed lower sucrose, glucose,

and fructose than the microwave-dried ones, as shown in Table 1. Fructose was the lowest in oven and microwave-dried plants, with 76.78 and 247.96 mg/100 g. In comparison, glucose was higher, with 389.63 and 725.26 mg /100 g on a dry basis in the same samples. The same trend was observed for the other saccharides, which are composed of several sugar units, such as sucrose, with a higher content in microwave-dried plants (966.84 mg/100 g on a dry basis).

Eleven fatty acid methyl esters were identified in fresh and dried samples, as shown in Table 1. In fresh plants, the six saturated fatty acids present constitute the major content of the extract, especially palmitic acid (34.93%) and stearic acid (16.49%), while linoleic acid (22.07%) and erucic acid (8.95%) were the major unsaturated fatty acids identified. The fatty acid composition of fresh plants indicates the potential precursors for the formation of lipid oxidation products in the profile of volatile compounds. A dramatic change could be observed upon oven drying of the plants, where linoleic acid increased to 59.25% at the expense of palmitic acid (14.89%) and stearic acid (7.11%). The same phenomenon could be observed to a lesser extent in microwaved plants, with 38.63% for linolenic acid, 26.15% for palmitic acid, and 13.10% for stearic acid, although one has to remember that the % of FAME was determined, not their amount expressed in mg/100 g of sample.

Discussion

The proximate analysis of fresh *S. oleraceus* plants generally agreed with the literature [5, 15]. According to Table 1, the moisture content of the fresh plants (90.44%) was higher than that obtained by Li and Yang [5] and lower than the results of Mohaseb et al. [15], which were 87.24 and 92.27%. Reduction in moisture content through drying processes, as shown in Table 1, enhances food digestibility, increases nutrient concentration, improves nutrient availability, extends shelf life, and inhibits microbial growth and autolytic enzymes [16].

The ash content of the fresh plants (18.51%) is higher than that of Mohaseb et al. [15], which presented 15.14%. Ash in food indicates the mineral content of the samples. Ash content reflects the total mineral amount in food [17]. When the ash content is compared for the examined samples, although they differ slightly, the differences are statistically insignificant.

Protein is a vital part of the diet required for the survival of both animals and humans, providing adequate essential amino acids. Li and Yang [5] showed a lower concentration (3.17%) in *S. oleraceus* fresh plants compared to the present study (25.57%) or that of Mohaseb et al. [15], which was 25.94%. The drying techniques applied in the current study showed significant differences in protein content compared to the fresh sample, indicating that drying may have a denaturing negative effect on protein content. The crude lipid content obtained by El-Tantawy [18] at 3.79% is in line with the results of the fresh plants detected in the current study (3.71%). The non-significant increase during drying, especially for oven-dried samples (3.89%), may be due to lipid oxidation, which Khaled et al. [19] reported during the drying of *Moringa oleifera* leaves with significant changes.

Furthermore, the carbohydrate content (44.155%) was lower than that obtained by Jimoh et al. [4], which represented 46.0% in plants of *S. oleraceus*. For carbohydrates, oven drying resulted in a substantial decrease in weight compared to the fresh and microwaved plants (Table 1). High drying temperatures can cause the breakdown of carbohydrates, particularly simple sugars such as glucose and fructose. These sugars may degrade through processes such as the Maillard reaction, which can reduce the overall carbohydrate content [20]. Human dietary fiber originates from plants, including fruits, vegetables, and seeds. A significant difference in crude fiber content was noted among fresh samples (8.05%), oven-dried samples (7.66%), and microwave-dried samples (7.425%). Crude fiber aids in peristalsis, supports bowel movement, lowers blood cholesterol, and reduces colon cancer risk [21]. Hot air drying reduces the molecular weight of soluble dietary fiber compared to freeze-drying [22].

Amino acids are the basic units of proteins and serve as an important nutritional quality in food. A total of 17 free amino acids of fresh and dried S. *oleraceus* plants are shown in Table 1. Generally, with the increase in temperature, total free amino acid content showed a declining trend in some of the essential amino acids such as tyrosine, cysteine, isoleucine, and phenylalanine, similar to previous reports [23]. In contrast, other amino acids of the dried plants listed in Table 1 like aspartic acid, glutamic acid, serine, glycine, proline, and methionine showed an increase compared to the fresh ones. In vacuum drying, high temperatures can increase free amino acids. Zhao et al. [24] found that microwave vacuum drying significantly boosts total free amino acids compared to fresh samples. The highest microwave power density resulted in maximum free amino acids due to elevated temperatures, indicating that thermal vacuum promotes proteolysis while preventing amino acid oxidation. Heating promotes the generation of free amino acids from proteins, as proteases hydrolyze proteins into smaller peptides and amino acids [25]. The Maillard reaction between amino acids and reducing sugars, noted in bee pollen, can reduce amino acid levels [26]. If the amino acids released from proteins exceed those consumed in the Maillard reaction, the final concentration will be higher than in fresh

samples. Similar findings regarding drying methods and total amino acid content in *Pleurotus eryngii* [27].

Table 1 shows the sugar profile of fresh and dried S. *oleraceus* plants. According to Alagbe et al. [28], increasing the drying temperature leads to greater moisture loss from the samples and favors the availability of carbohydrates in the dried plants. Consequently, higher total sugars were observed in the microwave- and oven-dried plants (1940.06 and 784.09 mg/100 g) compared to the fresh plants (721.22 mg/100 g on a dry basis). Sucrose, glucose, and fructose are the main soluble carbohydrates, and their quantities and ratios greatly influence the sensory quality of plants [29]. Sucrose is the primary sugar in ripe fruit, increasing during maturation, while lower levels of fructose and glucose either decrease or stay the same during ripening [30]. Oven-dried plants had significantly lower glucose and fructose than fresh and microwave-dried plants, likely due to high drying temperatures causing non-enzymatic browning [31]. It is especially noticeable in the decrease of fructose in oven drying, as fructose, due to its reactivity and amount of open form, is the favorite sugar ingredient in the Maillard reaction. The increase in particular sugars determined by HPLC when oven-dried samples are compared to microwave-dried plants can also be related to better extractability caused by microwaves compared to oven drying, which can cause tissue structure changes, which make sugar extraction more difficult.

In agreement with Guil-Guerrero et al. [32] and Chen et al. [33], high contents of linolenic acid, palmitic acid, and stearic acid were present in the fresh plants of *S. oleraceus*. However, the quantitative differences could be due to geographic and environmental variations among the study sites. According to Raksakantong et al. [34] and Hamza and Al-Hashimi [35], fatty acids could be changed significantly, as reported in the current study, due to the drying of kaffir lime or palm fruits, with an increase of unsaturated fatty acids such as linoleic acid on the expense of saturated ones like palmitic acid.

The strategy of simultaneous analysis of the volatile and the proximate analysis could give a better insight into the aroma and flavor changes during food processing. This study's results confirmed the significant effect of the drying technique on the volatile profile of *S. oleraceus*, as well as the potential association between these factors and the contents of potential precursors, such as proteins, carbohydrates, or lipids. The presented results of the main constituents and, more importantly, potential precursors of volatile compounds, such as free amino acids, particular mono and disaccharides, or the profile of FAME, enable a better understanding of the formation of volatiles explored herein. To our knowledge, using HS-SPME-GC × GC-TOFMS to evaluate the effect of the drying technique on the volatile profile yields the most comprehensive profile of S. oleraceus volatiles, representing the main novel point of the current study.

Compared to 127 volatiles identified in the present study, belong to 13 different classes (Table S1), Fukalova [9], in the most related study, extracted only 27 compounds from fresh *S. oleraceus* by HS/SPME before GC-MS analysis, with the domination of the benzenoid and aldehyde classes and the presence of benzeneacetaldehyde, 2-hexenal, and benzaldehyde as main components [9]. Most components of the previous study were detected in the present work, but there were dramatic quantitative differences due to variations in cultivation area and environmental conditions, as well as analytical techniques [36]. The selectivity of SPME fiber coatings can differ a lot, influencing the profile of extracted compounds. One must also remember that SPME extraction is time-dependent; therefore, varying the extraction time will also result in changes in the profile of the extracted compounds. Recently, El Gendy et al. [37] analyzed the hydrodistilled oil of *S. Oleraceus* aerial parts using GC-FID and GC-MS, where only 23 compounds were detected with nonadecane, methyl dihydrojasmonate, and caryophyllene as major components. The hydrodistillation technique for extracting essential oil volatiles, though assumed to be a standard method for essential oils analysis, may also suffer some drawbacks due to potential chemical changes, losses, and degradation of aroma compounds caused by heat, steam, and thermal or hydrolytic effects [38]. Consequently, many compounds have been detected for the first time in the present study and could be described as dominant in many classes. For example, 3-hexen-1-ol and 1-pentanol were among the major alcohols identified, with a contribution of 13 and 5% to the alcohol class. The dominant aldehydes of the present study, 2- and 3-methyl butanal, were not reported before. Twenty-seven terpenes were identified, most of them for the first time, especially monotypes like alpha- and beta-pinene, constituting 17 and 27% of the terpenes class identified. It is noteworthy that other groups, such as esters, O-heterocycles, and aliphatic hydrocarbons, were detected for the first time, in addition to most of the further classes' members, like ketones and N-heterocycles (Table S1, Fig. S1). Food drying improves safety and shelf life but alters sensory qualities. Drying can alter essential oils, producing new aroma compounds that may account for more than 50% of the volatiles, often due to cell wall rupture and oxidation [39].

Aldehydes became the predominant class among the others identified in both oven-dried and microwaved *S. oleraceus* plants, increasing from 15 components (9% of the total volatiles) in the fresh plants to 27 and 17 constituents in oven-dried (29%) and microwaved plants (30%), respectively (Fig. 2). New aldehydes in dried plants were

generated compared to fresh ones, such as alkenals (e.g., 2-methyl-2-butenal, 2-heptenal, and 2-ethyl-2-hexenal,), octanal, nonanal, undecanal, 2,6-nonadienal, and benzaldehyde derivatives (Table S1). On the other hand, the levels of common aldehydes in all samples, such as 2-methylbutanal, pentanal, and hexanal, increased after drying (Fig. S1, Table S1). Short-chain aldehydes such as 2-methylpropanal, 2- and 3-methylbutanal, in addition to benzaldehyde and benzene acetaldehyde derivatives, are formed through the Strecker degradation of amino acids or in the Maillard reaction induced by heat [40]. Meanwhile, the oxidation of unsaturated fatty acids is the main source of aldehydes (e.g., hexanal and octanal) and aldehydes with double bonds (alkenals and 2,4-alkadienals) derived from less stable acids [41].

To our knowledge, esters can be primarily derived through several pathways: the esterification between alcohols and acids to produce floral and fruity aromas, the metabolism during the whole dehydration process may also induce the production of esters, and the oxidation of fatty acids and degradation of amino acids [42]. Therefore, the contribution of esters to the total volatiles increased upon drying, from 14% in fresh plants to 16% and 19% in oven-dried and microwaved plants, respectively. Eight new esters were generated in dried plants compared to the fresh ones; two of them are branched (2,3-dimethyl butanoic acid ethyl ester and octanoic acid, 4-methoxyphenyl ester), while the others are straight-chain ones (Table S1).

In addition to 11 ketones identified in fresh plants, heating benefited the formation of 18 ketones in *S. oleraceus* plants through lipid oxidation, Maillard reaction, and degradation of amino acids, as shown in Table S1 [43]. In common, 2,3-butanedione and 3,5-octadien-2-one are among the dominant ketones identified in all analyzed samples. However, the drying process leads to the appearance of other dominants not found in fresh plants, such as 2-hexanone, 2-hydroxy-3-pentanone, 2-heptanone, 1-octen-3-one, 3-octen-2-one, 2-hexanone, 3-methyl-4-methylene-, and 2,3-octanedione (Fig. S1). Increased observed for diketones was reported to be formed by Maillard reaction intermediates through the fission of reductones [44].

Non-enzymatic browning, also known as the Maillard reaction, occurs during food drying, forming various aromas, particularly N- and O-heterocycles, through specific endoplasmic components. Yang et al. [45] examined the effects of various drying methods on green tea N and O-heterocycles. The results showed that box-type hot air convection drying produced the highest total N- and O-heterocycles content. In the current study, both groups constitute solid evidence for the Maillard reaction occurring during drying. N-heterocycles increased impressively from a single identified methylpyrazine in fresh *S. oleraceus* plants to 19 and 20 constituents in oven-dried and microwaved plants (Table S1). According to Fig. S1, 2-acetyl pyrrole, 2,6-dimethyl pyrazine, methyl pyrazine, 2-ethyl-3-methylpyrazine, and 2-ethyl-6-methyl pyrazine represent the main constituents of N-heterocycles in oven-dried plants. While 2,5-dimethyl pyrazine, 3-ethyl-2,5-dimethyl pyrazine, 2-ethyl-3-methyl pyrazine, 2-ethyl-6-methyl pyrazine, and 2-acetyl pyrrole were the dominants among N-heterocycles identified in microwaved plants. According to Yang et al. [45], the reaction of proline and 1-deoxy-2, 3-hexodiulose, through the phenylamine positive ion and decarboxylation-dehydration rearrangement, led to the formation of 2-acetyl pyrrole. Pyrazines are produced during thermal food processing and contribute to the unique flavors of meat, roasted, and cereal products. They are formed from the condensation of aminocarbonyls formed along with aldehydes in Strecker degradation of amino acids [46].

On the other hand, the drying process increases O-heterocycles' contribution from 5% (9 components) of the total volatiles identified in fresh plants to 9% (19 components) and 7% (14 components) in the oven-dried and microwaved *S. oleraceus* plants (Fig. 2). More furanones and pyrans were generated in dried samples, while tetrahydrofuran, acetylfuran, and butyrolactone were common in all analyzed samples (Table S1). Tetrahydrofuran and dihydro-5-methyl-2(3 H)-Furanone were the major O-heterocycles in fresh plants, while butyrolactone, 5-methyl-2-furfural, and tetrahydrofuran were the dominant ones in dried samples, but with quantitative differences between oven-dried and microwaved plants (Fig. S1). Multiple pathways lead to the formation of furan, including (i) thermal degradation or rearrangement of carbohydrates alone or in the presence of amino acids, (ii) thermal degradation of specific amino acids, (iii) oxidation of ascorbic acid at high temperatures, and (iv) oxidation of polyunsaturated fatty acids and carotenoids [47]. The Maillard reaction in an amino acid/glucose system yields an unstable methyl dicarbonyl intermediate known as l-deoxyosone via 2,3-enolization of the Amadori product. The l-deoxyosone is then easily enolized and cyclized, forming O-heterocyclic structures, such as pyranones [48]. Lactones can be formed from phenolic acids, carbohydrates, and carotenoids through parallel reactions such as the enolate Spengler-Pfannenstiel degradation and the Cannizzaro reaction of α-dicarbonyl compounds [49].

An increment in aliphatic hydrocarbons was observed upon drying, with comparable levels of aromatic hydrocarbons between fresh and dried plants (Fig. 2). 2-Butene, hexane, 4-tetradecene, and nonadecane constitute the main hydrocarbons in the analyzed samples. On the other hand, toluene, p-xylene, and azulene were the dominant aromatic hydrocarbons identified in fresh and dried plants (Table S1). Thermal degradation of saturated fatty acids results in the

formation of aliphatic hydrocarbons in the dried samples, as agreed by Raczyk et al. [50], who generated volatile hydrocarbons by thermal treatment of sterol esters with different fatty acid moieties. The diversities among hydrocarbons in the samples, such as absence or decrease, could be ascribed to the volatilization, degradation, and formation of compounds in fresh samples during the drying period (Table S1).

Fresh plants have no sulfur-containing compounds. In contrast, levels of the products formed via hydrolysis of S-methyl methionine or intermediates of methionine Strecker degradation [51], including dimethyl sulfide, dimethyl disulfide, bis[1-(methylthio)ethyl] disulfide, dimethyl sulfoxide, and dimethyl sulfone, were identified in the oven-dried sample. Only dimethyl sulfide and bis[1-(methylthio) ethyl] disulfide were detected in microwaved plants with a higher content compared to the oven-dried sample (Table S1). Similar results were observed in fresh black carrot as explored by Keskin and colleagues [52].

All the volatile classes identified in the present study were increased after *S. oleraceus* plants were dried at the expense of alcohols and terpenes (Table S1 and Fig. 2). Overall, the total levels of alcohol in oven-dried (18 alcohols) and microwaved (13 alcohols) plants were lower than those in the fresh ones (28 alcohols). The characteristic alcohols in drying samples were 3-buten-1-ol, 1-ethoxy-2-propanol, 4-methyl-1-pentanol, and 2-ethyl-1-hexanol, while those of fresh plants were 2-methyl-1-butanol, 2-hexen-1-ol, and 3-hexen-1-ol (Fig. S1). Except for newly generated alcohols: 3-buten-1-ol, 1-ethoxy-2-propanol, 1,6-heptadien-4-ol, 2-(2-ethoxyethoxy)-ethanol, 2-ethyl-1-hexanol, and 3-tetradecanol, a significant reduction in the abundances of the other common alcohols in all analyzed samples (Table S1). The diminution of alcohols may be attributed to volatilization and esterification under exposure to heat [53]. Meanwhile, the oxidative decomposition of fat, the Ehrlich pathway from amino acids, and the reduction of carbonyl compounds were the main reasons for the increase in some alcohols [54].

Compared to the fresh *S. oleraceus* plants, which have 27 terpenes and account for 22% of the total volatiles, a reduction was observed in the terpene contents of dried samples. Oven-dried and microwaved samples have only 20 and 19 constituents, with 12 and 8% of the total volatiles identified (Fig. 2). During the drying processes, the terpenoids in samples might be directly produced or transformed from initial products of sesquiterpenes or monoterpenes through dehydrogenation, oxidation, and other reactions [55]. Thus, the abundances of monoterpenes like α-pinene, camphene, and β-pinene were augmented in the dried plants. In addition, new monoterpenes and sesquiterpenes were generated in dried samples: dihydromyrcenol, β-cyclohomocitral, anethole, β-elemene, β-caryophyllene, β-farnesene, and β-ionone (Table S1). However, the application of heat and energy during dehydration can result in the degradation of terpenes [42], which explains the decrease in isoprene concentration in the dried samples (Table S1). The previous findings agreed with the results of Hazrati et al. [56] and Mahmoud et al. [57], who dried *Stachys lavandulifolia* and the postharvest waste of *Ocimum basilicum* using different drying methods, which had a negative effect on the amounts of hydrocarbon monoterpenes and sesquiterpenes identified in the oil extracted from the dried plants.

Conclusion

The study investigates the impact of oven and microwave drying on the volatile compounds and nutrients in *Sonchus oleraceus* L., a Mediterranean leafy vegetable. Drying significantly increased the protein and fat contents but reduced the crude fiber content. However, it significantly lowers the levels of key amino acids, including tyrosine, cysteine, isoleucine, and phenylalanine, due to Maillard reactions. Compared to microwave-dried samples, oven-dried plants contain less sucrose, glucose, and fructose, indicating greater sugar utilization in thermal processes. On the other hand, the fatty acid profile changed upon drying, with the predominance of palmitic, stearic, linolenic, and erucic acids. Fresh plants are rich in alcohols, terpenes, and esters, with drying leading to an increase in aldehydes, ketones, and Maillard reaction products, which correspond to a decrease in amino acids and sugars. Sulfur compounds suggest methionine degradation. The study highlights the effect of drying on plants' nutrients and their roles in generating aroma, which accompanies changes in their concentration. These findings provide insights into optimizing drying methods to enhance safety, shelf life, and sensory quality.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors have no conflicts of interest to be declared.

Ethical approval This study did not involve animal or human subjects.

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References

1. - Vanzani P, Rossetto M, De Marco V, Sacchetti LE, Paoletti MG, Rigo A (2011) Wild mediterranean plants as traditional food: a valuable source of antioxidants. J Food Sci 76(1):C46–C51. https://doi.org/10.1111/j.1750-3841.2010.01949.x
2. - García-Herrera P, Morales P, Cámara M, Fernández-Ruiz V, Tardío J, Sánchez-Mata MC (2020) Nutritional and phytochemical composition of mediterranean wild vegetables after culinary treatment. Foods 9(12):1761. https://doi.org/10.3390/foods9121761
3. - Cameron EK (2000) Native Sow thistle, Sonchus kirkii, rediscovered in the Auckland region. Auckl Bot Soc J 55(1):21–24
4. - Jimoh FO, Adedapo AA, Afolayan AJ (2011) Comparison of the nutritive value, antioxidant and antibacterial activities of Sonchus Asper and Sonchus oleraceus. Rec Nat Prod 5(1):29–42
5. Li -, X. M., Yang PL (2018) Research progress of Sonchus species. Int J Food Prop 21(1):147–157. https://doi.org/10.1080/10942912.2017.1415931
6. El-Desouky TA (2021) Evaluation of effectiveness aqueous extract for some leaves of wild edible plants in Egypt as antifungal and anti-toxigenic. Heliyon 7(2). https://doi.org/10.1016/j.heliyon
7. - Yin J, Kwon GJ, Wang MH (2007) The antioxidant and cytotoxic activities of Sonchus oleraceus L. extracts. Nutr Res Pract 1(3):189–194
8. - Vilela FC, Bitencourt AD, Cabral LD, Franqui LS, Soncini R, Giusti-Paiva A (2010) Anti-inflammatory and antipyretic effects of Sonchus oleraceus in rats. J Ethnopharmacol 127(3):737–741
9. - Fukalova Fukalova T, Moreno-Peris E, García-Martínez MD, Raigón Jiménez MD (2022) Assessment of the volatile profiles and identification of differentiating aromas of wild undervalued plants. Front Nutr 9:912680. https://doi.org/10.3389/fnut.2022.912680
10. - Drabińska N, Siger A, Jeleń H (2023) Comprehensive two-dimensional gas chromatography-time of flight mass spectrometry as a tool for tracking roasting-induced changes in the volatilome of cold-pressed rapeseed oil. Anal Bioanal Chem 415(13):2523–2534. https://doi.org/10.1007/s00216-022-04486-6
11. - Zhang P, Piergiovanni M, Franceschi P, Mattivi F, Vrhovsek U, Carlin S (2023) Application of comprehensive 2D gas chromatography coupled with mass spectrometry in beer and wine VOC analysis. Analytica 4(3):347–373. https://doi.org/10.3390/analytica4030026
12. - Ou ZQ, Schmierer DM, Strachan CJ, Rades T, McDowell A (2014) Influence of postharvest processing and storage conditions on key antioxidants in Pūhā (*Sonchus oleraceus* L). J Pharm Pharmacol 66(7):998–1008. https://doi.org/10.1111/jphp.12220
13. AOAC (2000) Official methods of analysis of AOAC international, 10th edn. AOAC International, St. Paul, MN, USA
14. - Razal RA, Lewis NG, Towers GN (1994) Pico-tag analysis of arogenic acid and related free amino acids from plant and fungal extracts. Phytochem Anal 5(3):98–104. https://doi.org/10.1002/pca.2800050303
15. - Mohasib RM, Nagib A, Samad AA, Salama ZA, Gaafar AA, Taie HA, Hussein SR (2020) Identification of bioactive ingredients in Sonchus oleraceus by HPLC and GC/MS
16. - Garba ZN, Oviosa S (2019) The effect of different drying methods on the elemental and nutritional composition of Vernonia amygdalina (bitter leaf). J Taibah Univ Sci 13(1):396–401. https://doi.org/10.1080/16583655.2019.1582148
17. - Agoreyo BO, Akpiroroh O, Orukpe OA, Osaweren OR, Owabor CN (2011) The effects of various drying methods on the nutritional composition of Musa paradisiaca, Dioscorea rotundata and colocasia esculenta. https://doi.org/10.3923/ajb.2011.458.464
18. El-Tantawy H (2002) The nutritional value of some desert plants in kuwait, Arabian pennisula. Taeckholmia 22(1):35–45
19. - Khaled BM, Das AK, Alam SS, Saqib N, Rana MS, Sweet SR, Yesmin A (2024) Effect of different drying techniques on the physicochemical and nutritional properties of Moringa Oleifera leaves powder and their application in bakery product. Appl Food Res 4(2):100599. https://doi.org/10.1016/j.afres.2024.100599
20. - Choudhary A, Kumar V, Kumar S, Majid I, Aggarwal P, Suri S (2021) 5-Hydroxymethylfurfural (HMF) formation, occurrence and potential health concerns: recent developments. Toxin Reviews 40(4):545–561. https://doi.org/10.1080/15569543.2020.1756857
21. - Ojo A, Abiodun OA, Odedeji JO, Akintoyese OA (2014) Effects of drying methods on proximate and Physico-chemical properties of Fufu flour fortified with soybean. British J Appl Science Technology 4(14):2079–2089. https://doi.org/10.9734/BJAST/2014/8984
22. - Liu Y, Fan C, Tian M, Yang Z, Liu F, Pan S (2017) Effect of drying methods on physicochemical properties and in vitro hypoglycemic effects of orange Peel dietary fiber. J Food Process Preserv 41(6):e13292. https://doi.org/10.1111/jfpp.13292
23. - Babiker EE, Juhaimi FA, Ghafoor K, Abdoun KA (2018) Effect of drying methods on nutritional quality of young shoots and leaves of two Moringa species as non-conventional fodders. Agroforest Syst 92:717–729
24. - Zhao Y, Jiang Y, Zheng B, Zhuang W, Zheng Y, Tian Y (2017) Influence of microwave vacuum drying on glass transition temperature, gelatinization temperature, physical and chemical qualities of Lotus seeds. Food Chem 228:167–176
25. - Xiang Y, Zou M, Ou F, Zhu L, Xu Y, Zhou Q, Lei C (2024) A comparison of the impacts of different drying methods on the volatile organic compounds in ginseng. Molecules 29(22):5235
26. - Bi Y, Ni J, Xue X, Zhou Z, Tian W, Orsat V, Fang X (2024) Effect of different drying methods on the amino acids, α-dicarbonyls and volatile compounds of rape bee pollen. Food Sci Hum Wellness 13(1):517–527. https://doi.org/10.26599/FSHW.2022.9250045
27. - Li X, Feng T, Zhou F, Zhou S, Liu Y, Li W, Yang Y (2015) Effects of drying methods on the tasty compounds of pleurotus eryngii. Food Chem 166:358–364. https://doi.org/10.1016/j.foodchem.2014.06.049
28. - Alagbe EE, Amlabu YS, Daniel EO, Ojewumi ME (2020) Effect of varying drying temperature on the soluble sugar and nutritional

content of banana. Open Chem Eng J 14(1). https://doi.org/10.2174/1874123102014010011
29. - Zhang XM, Dou MA, Yao YL, Du LQ, Li JG, Sun GM (2011) Dynamic analysis of sugar metabolism in different harvest seasons of pineapple (Ananas comosus L.(Merr)). Afr J Biotechnol 10(14):2716–2723
30. - Beaulieu JC, Lea JM, Eggleston G, Peralta-Inga Z (2003) Sugar and organic acid variations in commercial cantaloupes and their inbred parents. J Am Soc Hortic Sci 128(4):531–536
31. - Mongi RJ, Ngoma SJ (2022) Effect of solar drying methods on proximate composition, sugar profile and organic acids of Mango varieties in Tanzania. Appl Food Res 2(2):100140. https://doi.org/10.1016/j.afres.2022.100140
32. - Guil-Guerrero JL, Giménez-Giménez A, Rodríguez-García I, Torija-Isasa ME (1998) Nutritional composition of species *Sonchus* (*S Asper* L, *S oleraceus* L and *S tenerrimus* L). J Sci Food Agric 76(4):628–632
33. - Chen C-Y, Su CW, Li X, Liu Y, Pan Q, Cao T, Kang JX (2021) Lipid extract from a vegetable (*Sonchus Oleraceus*) attenuates adipogenesis and high fat Diet-Induced obesity associated with AMPK activation. Front Nutr 8:624283. https://doi.org/10.3389/fnut.2021.624283
34. - Raksakantong P, Siriamornpun S, Meeso N (2012) Effect of drying methods on volatile compounds, fatty acids and antioxidant property of Thai Kaffir lime (*Citrus hystrix* D.C). Int J Food Sci Technol 47:603–612. https://doi.org/10.1111/j.1365-2621.2011.02883.x
35. Hamza RS, Al-Hashimi AG (2023) Effect of different drying methods on some mineral elements, amino acids and fatty acids of the fruits of some Iraqi palm cultivars. BIODIVERSITAS 24(1):359–369
36. - Boudechicha A, Aouf A, Farouk A, Ali HS, Elkhadragy MF, Yehia HM, Badr AN (2023) Microfluidizing technique application for Algerian cymbopogon citratus (DC.) Stapf effects enhanced volatile content, antimicrobial, and anti-mycotoxigenic properties. Molecules 28(14):5367. https://doi.org/10.3390/molecules28145367
37. Gendy AENG, Mohamed NA, Sarker TC, Hassan EM, Garaa AH, Elshamy AI, Abd-ElGawad AM (2024) Chemical composition, antioxidant, and cytotoxic activity of essential oils in the Above-Ground parts of Sonchus oleraceus L. Plants 13(12):1712. https://doi.org/10.3390/plants13121712
38. - Khajeh M, Yamini Y, Sefidkon F, Bahramifar N (2004) Comparison of essential oil composition of carum Copticum obtained by supercritical carbon dioxide extraction and hydrodistillation methods. Food Chem 86(4):587–591. https://doi.org/10.1016/j.foodchem.2003.09.041
39. - Xing Y, Lei H, Wang J, Wang Y, Wang J, Xu H (2017) Effects of different drying methods on the total phenolic, Rosmarinic acid and essential oil of purple Perilla leaves. J Essent Oil Bearing Plants 20(6):1594–1606. https://doi.org/10.1080/0972060x1413957
40. Wang H, Zhang Q, Mujumdar AS, Fang XM, Wang J, Pei YP, H.W. Xiao (2020) High-humidity hot air impingement blanching (HHAIB) efficiently inactivates enzymes, enhances extraction of phytochemicals and mitigates brown actions of Chili pepper. Food Control 111:107050
41. - Shahidi F, Hossain A (2022) Role of lipids in food flavor generation. Molecules 27(15):5014
42. - Guclu G, Keser D, Kelebek H, Keskin M, Sekerli YE, Soysal Y, Selli S (2021) Impact of production and drying methods on the volatile and phenolic characteristics of fresh and powdered sweet red peppers. Food Chem 338:128129
43. - Yang XH, Deng LZ, Mujumdar AS, Xiao HW, Zhang Q, Kan Z (2018) Evolution and modeling of colour changes of red pepper (Capsicum annuum L.) during hot air drying. J Food Eng 231:101–108
44. - Poisson L, Blank I, Dunkel A, Hofmann T (2017) The chemistry of roasting—Decoding flavor formation. The craft and science of coffee. Academic, pp 273–309
45. Yang Y, Xie J, Chen J, Deng Y, Shen S, Hua J, Jiang Y (2022) Characterization of N, O-heterocycles in green tea during the drying process and unraveling the formation mechanism. Food Control 139:109079. https://doi.org/10.1016/j.foodcont.2022.109079
46. - Zhao C, Cao H, Xiao J (2020) Pyrazines in food. In: Xiao J, Sarker S, Asakawa Y (eds) Handbook of dietary phytochemicals. Springer, Singapore. https://doi.org/10.1007/978-981-13-1745-3_44-1
47. Seok YJ, Her JY, Kim YG, Kim MY, Jeong SY, Kim MK, Lee KG (2015) Furan in thermally processed foods-a review. Toxicol Res 31:241–253. https://doi.org/10.5487/TR.2015.31.3.241
48. - Lertsiri S, Fujimoto K, Miyazawa T (1995) Pyrone hydroperoxide formation during the Maillard reaction and its implication in biological systems. Biochim Et Biophys Acta (BBA)-General Subj 1245(3):278–284. https://doi.org/10.1016/0304-4165(95)00129-8
49. - Cherepanov IS, Botalova OO (2020), November Lactones formation during monosaccharide's caramelization in ethanolic-aqueous solutions. In *AIP Conference Proceedings* (Vol. 2280, No. 1). AIP Publishing
50. - Raczyk M, Kmiecik D, Schieberle P, Przybylski R, Jeleń H, Rudzińska M (2017) Model studies on the formation of volatile compounds generated by a thermal treatment of Steryl esters with different fatty acid moieties. Food Res Int 97:87–94
51. - Luo D, Pang X, Xu X, Bi S, Zhang W, Wu J (2018) Identification of cooked off-flavor components and analysis of their formation mechanisms in melon juice during thermal processing. J Agric Food Chem 66(22):5612–5620
52. Keskin M, Guclu G, Sekerli YE, Soysal Y, Selli S, Kelebek H (2021) Comparative assessment of volatile and phenolic profiles of fresh black Carrot (Daucus Carota L.) and powders prepared by three drying methods. Sci Hort 287:110256
53. - Guo Y, Chen D, Dong Y, Ju H, Wu C, Lin S (2018) Characteristic volatiles fingerprints and changes of volatile compounds in fresh and dried tricholoma Matsutake singer by HS-GC-IMS and HS-SPME-GC–MS. J Chromatogr B 1099:46–55
54. Schwab W, Davidovich-Rikanati R, Lewinsohn E (2008) Biosynthesis of plant-derived flavor compounds. Plant J 54(4):712–732
55. - Wen R, Hu Y, Zhang L, Wang Y, Chen Q, Kong B (2019) Effect of NaCl substitutes on lipid and protein oxidation and flavor development of Harbin dry sausage. Meat Sci 156:33–43
56. - Hazrati S, Lotfi K, Govahi M, Ebadi MT (2021) A comparative study: influence of various drying methods on essential oil components and biological properties of stachys Lavandulifolia. Food Sci Nutr 9(5):2612–2619. https://doi.org/10.1002/fsn3.2218
57. - Mahmoud E, Starowicz M, Ciska E, Topolska J, Farouk A (2022) Determination of volatiles, antioxidant activity, and polyphenol content in the postharvest waste of ocimum Basilicum L. Food Chem 375:131692. https://doi.org/10.1016/j.foodchem.2021.131692

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