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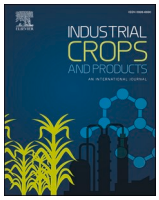

Impact of drying processes on volatilome and bioactive compounds in Damask and Centifolia moss roses and recovering of condensed waters

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ABSTRACT

The importance of roses in the cosmetic, pharmaceutical and food sectors relies on their aromatic and volatile compounds. However, rose fresh flowers rapidly degrade, losing their phytochemical characteristics and fragrance. The composition of volatile organic compounds (VOCs) and the antioxidant activity of three roses, i.e., one Damask rose (*Rosa* × *damascena* Mill.), and two Centifolia roses, namely Moss rose (*Rosa* × *centifolia* f. *muscosa* (Ait.) C.K.Schneid.) and Valle Scrivia moss rose landrace, were assessed in fresh flowers and in dried flowers obtained through hot-air drying (HAD) and heat-pump drying (HPD) methods, and in the condensed waters recovered from this latter. The three roses were rich in phenylethyl alcohol and terpenoids, although each one showed peculiar profiles. Hot-air drying gave better results for the Moss and Valle Scrivia roses, better preserving monoterpenes and phenylpropanoids, while heat-pump drying gave better results for Damask rose, better preserving the phenyl derivatives and monoterpenes. This drying method also allowed the recovering of rose waters, which displayed interesting aroma compounds, such as the phenylethyl alcohol, making them suitable for food and cosmetic applications. This study provides the first genotype-specific evaluation of drying methods for damask and moss roses, establishing a basis for targeted post-harvest processing.

1. Introduction

The rose is one of the most important crops in the floriculture industry. Its economic importance relies on its ornamental value as cut flowers or garden plants, but also on its content in aromatic and volatile organic compounds (VOCs), which are widely used in food, perfume, cosmetic, and pharmaceutical industries (Faur et al., 2024; Hegde et al., 2022; Koksal et al., 2015). The main factors determining the aromatic profile in roses are the structure and concentration of VOCs (Caser and Scariot, 2022; Martínez et al., 2020). In particular, this generates substantial varietal differences among rose fragrances in terms of aroma characteristics, quality, intensity, and persistence, with varying levels of compounds, such as citronellol, geraniol, nerol, linalool, and phenylethyl alcohol (Martínez et al., 2020).

Regarding the flavouring and food industries, confectioneries and beverages, such as biscuits, cakes, teas or jams are often flavoured with rose water, for its aromatic and volatile characteristics, as well as rose oil for its fragrance (Geng et al., 2020; Önder et al., 2022). In addition to the more traditional uses, rose flowers are increasingly proposed as functional food, since they contain bioactive compounds like polyphenols, anthocyanins, organic acids, fatty oils, pectins, carotenoids, tocopherols, giving these flowers high antioxidant activity, which enhances human well-being, helping in the prevention of oxidative stress disorders (Devecchi et al., 2021; Hegde et al., 2022; Kunc et al., 2024).

Over 200 *Rosa* species and 25.000 cultivars with a very complex hybrid origin are present (Cock et al., 2007; Scariot et al., 2006), expressing different ornamental and phytochemical characteristics (Faur et al., 2024; Hegde et al., 2022; Martínez et al., 2020). Only a few are cultivated for industrial purposes, such as *R. gallica* L. and *R. rugosa* Thunb., and particularly *R.* × *damascena* and *R.* × *centifolia* (Koksal et al., 2015; Qiu et al., 2020).

Rosa × *damascena*, commonly known as Damask rose, is an ancient cultivated rose, particularly appreciated and used to obtain distillation products, such as rose water, rose absolute and rose concrete, mainly used in the cosmetic industry, or rose oil, mainly used in perfume and food industries (Önder et al., 2022).

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Rosa × *centifolia,* commonly known as Rose de Mai, Provence rose or cabbage rose, constituted the primary source of raw material for the rose essence industry of the 19th century in Europe (Martínez et al., 2020). This species comprises various forms and varieties, such as *R.* × *centifolia* f. *muscosa*, a mossy sport obtained by bud mutation from *R.* × *centifolia* (Caissard et al., 2006), commonly known as Moss rose, and in Italy, a landrace named "Valle Scrivia" according to its native geographic valley (Liguria region, North-Western Italy).

Rose flowers, however, undergo a rapid degradation, maintaining freshness only for a brief period, losing their bioactive and VOCs, therefore being difficult to transport and store (Qiu et al., 2020). To maintain them longer, drying is an effective method already applied on foods (Ansar and Akbolat, 2017; Geng et al., 2020; Salamatullah et al., 2024). The drying process implies the removal of water content from the rose petals to prevent microbial growth and enzymatic degradation, it preserves their bioactive compounds, and reduces the weight of the flowers, thereby facilitating transport and storage (Demasi et al., 2023; Qiu et al., 2020)). However, it must always be considered that drying is a complex biochemical process possibly inducing undesirable changes in primary and secondary metabolites and if proper dehydration technology is not applied, roses may lose their olfactory intensity and quality (Ansar and Akbolat, 2017; Fernandes et al., 2018). Therefore, the selection of an appropriate drying technology is crucial for obtaining dried products with optimal quality (Fernandes et al., 2018; Qiu et al., 2020). Different drying methods have already been applied on roses, e.g. sun drying (i.e., the exposure of flowers to the sun in the open air), hot air drying (i.e., flowers are oven-dried at high temperatures for hours), vacuum freeze-drying (i.e., the moisture is removed by sublimation) (Bian et al., 2024; Qiu et al., 2020).

Traditionally, the hot air drying (HAD) method is mostly used on fresh roses, set at an appropriate temperature, while rose water is extracted through steam distillation of the fresh flowers (Geng et al., 2020). However, heat application on roses, though simple and low cost, may cause changes in the phytochemical composition of the flowers, which are extremely sensitive to heat, thus affecting the final flavour, colour, bioactive compounds content and fragrance in the dried product (Bian et al., 2024; Demasi et al., 2023; Fernandes et al., 2018). On the other hand, freeze-drying showed a better quality of the final product, with low degradation of colour, flavour and nutritional properties, but the drying process is long, thus requiring high energy consumption (Qiu et al., 2020).

Heat-pump drying (HPD) is a convection air dryer that cools an airstream, drying the air by condensing the water vapor contained in it, while preserving the nutritional and sensory properties of the food. The evaporated moisture and VOCs can then be recovered, as well as heat, making it an environmentally friendly, closed-controlled system with high energy efficiency (Demasi et al., 2023; Deymi-Dashtebayaz et al., 2024; Geng et al., 2020). This technology has already been successfully applied on edible flowers (Ansar and Akbolat, 2017; Caser et al., 2023; Demasi et al., 2023; Falla et al., 2022; Geng et al., 2020), however, little is known about the effect of this process on the bioactive and volatile compounds of dried roses.

Due to the importance of roses in the cosmetics, pharmaceuticals and food industries, we first explored the composition of VOCs and the antioxidant activity in the flowers of the Damask rose, the Moss rose and the Valle Scrivia moss rose landrace, in order to assess their quality. Due to the lack of comparative data on genotype-dependent responses to drying methods for Damask and Moss roses, we then evaluated the effects of HAD and HPD on the phytochemical profiles of these roses. We assumed that HPD would preserve quality better than HAD, resulting in lower phytochemical degradation and VOC volatilisation, while also recovering valuable rose waters.

2. Materials and methods

2.1. Plant material

Rosa × *damascena* Mill., *Rosa* × *centifolia* f. *muscosa* (Ait.) C.K. Schneid., *Rosa* × *centifolia* f. *muscosa* landrace "Valle Scrivia", hereafter referred to as Damask rose, Moss rose and Valle Scrivia rose, respectively, were grown and harvested in full bloom in the nursery "JB Rose Farm" (Ronco Scrivia, Italy; 44°36'7.8948'' N, 8°58'44.8716'' E). Rose petals were separated manually from the rest of the flower and then transferred to the laboratory, preserved in plastic bags in portable refrigerators, on the same day of harvest. One part was stored at −80°C for phytochemical analysis, while the other part was dried. The moisture content of fresh rose flowers, measured by an oven at 60°C (AOAC, 2005) gave a similar average value of 84.4%, 88.6%, 86.7% respectively for Damask, Moss and Valle Scrivia roses.

2.2. Drying method

Two different drying methods, i.e., hot-air drying (HAD) and heat-pump drying (HPD), were applied on rose edible flowers.

Regarding HAD, the flowers were uniformly arranged on aluminium trays in single layers and then dried for 4–6 h at 60°C in a laboratory stove (VWR Stoves, Milan, Italy), according to literature range (Geng et al., 2020; Bian et al., 2024).

Regarding HPD, the flowers were uniformly arranged in single layers on perforated plastic trays, and then dried for 24 h at 30°C through refrigeration equipment that cools and dehydrates air (NWT-5, North West Technology, Boves—CN, Italy, 0.45 kW, 50 Hz). The humidity rate was kept constant at 5–6%. Since heat-pump drying allows the recovery of flavoured condensed waters resulting from the dehydration treatment of flowers, after drying, the condensed waters of roses were analysed to assess their potential.

The duration of the entire process was defined for both drying methods by assessing the flowers' weight at regular intervals until it remained constant and until the moisture content reached about 3–5% of humidity for the three group of samples to better stress rose flowers maintaining.

Dried flowers were then stored in plastic bags at room temperature.

2.3. Extracts

The extraction process was performed using 1 g of fresh flower in 10 mL of acidified ultrapure water (0.013 N H_2SO_4). The mixture was agitated at 120 rpm in the dark for 30 min. Subsequently, the resulting extract was centrifuged at 10,000 rpm and 10 °C for 15 min and the supernatant was filtered through 0.22 μm cellulosic membrane syringe filters. The extracts were stored at −20 °C until analysis.

2.4. Phytochemical analysis

Total phenolic content (TPC) and antioxidant activity (AOA) of fresh and dried rose flowers were evaluated through colorimetric methods using a Cary 60 UV-Vis spectrophotometer (Agilent, Santa Clara, CA, USA), as reported in previous studies (Demasi et al., 2021a; 2021b).

TPC was analysed following the Folin–Ciocalteu method (Demasi et al., 2021a; 2021b): briefly, 200 μL of extract were mixed with 1000 μL of diluted (1:10) Folin–Ciocalteu's reagent. Samples were left in the dark at room temperature for 10 min, and then 800 μL of Na_2CO_3 (7.5%) were added. After a further 30 min in the dark at room temperature, absorbance was read at 765 nm. The results were compared with a calibration curve constructed using gallic acid as a standard (1.95–250 mg L−1; R2 = 0.9982), and they were expressed as milligrams of gallic acid equivalents per 100 g of dry weight (mg GAE/100 g DW).

AOA was analysed using the 2,2-diphenyl-1-picrylhydrazyl (DPPH) assay (Demasi et al., 2021a; 2021b). Briefly, the working solution of

DPPH radical cations (DPPH, 100 μM) was obtained by dissolving 2 mg of DPPH in 50 mL of MeOH. The absorbance at 515 nm of the DPPH solution was corrected to a value of 1000 (±0.005) by adding MeOH. Then, 20 μL of flower extract (or extraction solvent for the control sample) was mixed with 1.5 mL of the DPPH radical solution. After 30 min in the dark at room temperature, the absorbance was read at 515 nm.

The radical scavenging activity was calculated as:

$$[(Abs0 - Abs1)/Abs0] \times 100$$

where Abs0 is the absorbance of the control sample and Abs1 is the absorbance of the

sample containing the flower extract. The values were plotted against a Trolox calibration

curve (0.0078–1 μg μL−1; R2 = 0.9626). Results were expressed as micromoles of Trolox Equivalents per 1 g of dry weight (μmol TE/g DW).

2.5. Profiling of volatile organic compounds

The VOCs were evaluated on fresh and dried rose petals, and on condensed water from all three groups of rose flowers. The VOCs were extracted using headspace solid phase microextraction (HS-SPME), analysed, identified and quantified using gas chromatography coupled with a quadrupole spectrometer (GC-*q*MS).

For the VOCs, 0.25 g of fresh or dried whole petals were weighted in 20 mL vial, along with either 1 g of 30% NaCl solution (27800.291, VWR, U.S.A.) or 1 g of condensed rose water; then 10 μL of 1,3,5-tris(1-methylethyl) benzene (94.4 mg/kg) were added as internal standard (IS). Four replicates were carried out for each sample. The vials were immediately sealed with a PTFE-silicon septum. The extraction was performed using an AOC−5000 CombiPAL Autosampler for SPME (CT Analytics AG, Zwingen, CH) equipped with an HS-SPME unit. Samples were conditioned at 50 °C for 15 min.

The SPME fibre coated with divinylbenzene/carboxen/polydimethylsiloxane (Supelco, Belfonte, Pennsylvania, USA) was then exposed to the headspace of the sample at 50°C for 30 min. The fibre was then desorbed into the injection port of the GC system in split mode at 260°C.

GC-qMS analyses were performed using a Shimadzu GC−2010 gas chromatograph with a quadrupole spectrometer (Shimadzu Corporation, Kyoto, JP). The VOCs were separated on an RTX−5 capillary column (20 m length; 0,10 mm diameter and 0,10 μm film thickness). The oven time temperature was programmed as follows: 40°C for 1 min; then increasing from 40°C to 220°C at a rate of 5 °C/min; then increasing to 250°C at a rate of 10 °C/min; then increasing to 300°C at a rate of 20 °C/min. The final temperature was then held for 5 min. The carrier used was helium, supplied at a constant flow rate of 0.65 mL/min in split injection mode (1:15). The MS fragmentation was performed by electronic ionization (EI) mode (70 eV), with the ion source and quadrupole temperatures set to 200°C. Data were recorded in full-scan mode within the mass acquisition range of 33–300, with a 0.30 s scan time (Barbosa-Pereira et al., 2019).

The identification of the volatile organic compounds was performed by comparing the EI-MS fragmentation patterns of each compound with those available in the National Institute of Standards and Technology (NIST17) mass-spectral library, chemical standards, and Retention Indices (RI) (see Table S1). The semi-quantitative concentrations of the identified VOCs were calculated by dividing the area of each volatile component by the response factor of the added internal standard, and were then expressed as micrograms of internal standard equivalents per kilogramme of sample (μg IS eq./kg of sample). Data were acquired and analysed using GC-MS Solution Workstation software (version 4.3) (GC-MS Solution, Shimadzu Corporation, Kyoto, JP).

2.6. Statistical analysis

Data for TPC and AOA were first tested for the homogeneity of variances (Levene test, $p \geq 0.05$).

Differences among the three fresh roses (TPC and AOA) and the effects of both drying methods on phytochemicals (TPC and AOA), volatile compounds and rose species were computed through a one-way ANOVA.

Means were separated according to the Ryan–Einot–Gabriel–Welsch F post hoc test (REGW-F, $p \leq 0.05$). When the ANOVA assumptions were not expected, data were analysed with the Kruskal–Wallis ($p < 0.05$) via stepwise comparison.

These statistical analyses were computed by SPSS software (version 28.0, SPSS Inc., Chicago, IL, USA).

The principal component analysis (PCA) and the heatmap were performed in R (R Core Team 2025). Volatile organic compound concentrations (μg/kg) were handled as non-negative, right-skewed variables; therefore, data were log-transformed as $\log10(x+1)$ prior to multivariate analyses (PCA and hierarchical clustering) to stabilize variance and reduce the leverage of highly abundant compounds. Missing values were treated as non-detects and set to zero before transformation.

PCA was used to summarize the main sources of variation in volatile profiles. PCA was computed on the set of VOCs after transformation and Pareto scaling (mean-centring and division by $\sqrt{SD}$ per compound), a chemometric scaling that down-weights very high-variance variables while preserving relative structure compared with full autoscaling. PCA was performed via singular value decomposition (base R function prcomp), and the percentage of variance explained by each principal component (PC) was calculated from eigenvalues. Variable representation in the PC1–PC2 plane was quantified using $\cos^2$, computed as the sum of squared correlations between each active variable and the PC scores for PC1 and PC2. For interpretability in the biplot, only active variables with $\cos^2(PC1 + PC2) > 0.70$ were displayed. A set of supplementary (passive) variables (i.e., the sums of VOCs) was projected onto the PCA space without influencing the PCA solution. After $\log10(x+1)$ transformation, each passive variable was correlated (Pearson correlation) with the PC1 and PC2 sample scores. Passive variables were thus interpreted as associations with the existing PCA axes rather than contributors to axis construction.

To visualize multivariate patterns across samples and compounds, a heatmap was generated from the log-transformed data further standardized by compound (column-wise z-scores; mean-centred and scaled to unit variance). Sample-to-sample dissimilarities were computed using Bray–Curtis distance on the log-transformed matrix (function vegdist in vegan package, (Oksanen et al., 2024), which is appropriate for non-negative abundance-like data and is robust to sparsity (many zeros). Hierarchical agglomerative clustering of samples was performed using average linkage (UPGMA; base R function hclust). To cluster compounds by similarity in their across-sample profiles, a Spearman rank correlation matrix was computed between compounds on the log-transformed data, and converted to a dissimilarity matrix as $1 - \rho$. Compound clustering was then performed using hierarchical agglomerative clustering with average linkage (base R function hclust).

3. Results and discussion

3.1. Total phenolic content and antioxidant activity

3.1.1. Fresh flowers

The three different rose flowers showed differences in TPC (from 3482.48 to 5179.49 mg/100 g DW) and DPPH (from 82.48 to 149.11 μmol TE/g DW) (Fig. 1). Valle Scrivia rose showed the highest TPC value, as well as high DPPH.

The TPC values are similar to those obtained by Shameh and colleagues (2018) in other *Rosa* species, namely *R. canina* L., *R. moschata* Herrm., *R. damascena*, *R. webbiana* Wall. ex Royle,

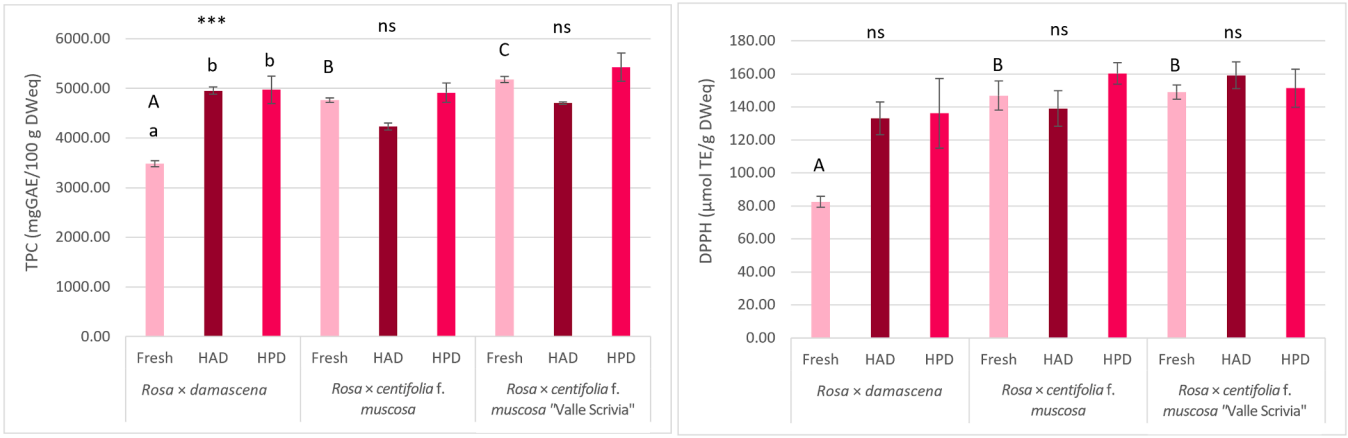


Fig. 1. Total Phenolic Content (TPC) and antioxidant activity (DPPH) of fresh and dried (Hot-air dried – HAD - and heat-pump dried - HPD) rose petals. Asterisks indicate significant differences among fresh and dried flowers in the single species. Small case letters indicate differences among fresh, and HAD and HPD flowers, in the single species; capital letters indicate differences among the three fresh roses. Significance is provided. *** = $p \leq 0.001$.

R. hemisphaerica Herrm., and *R foetida* Herrm., which ranged from 2513 to 5201 mg GAE/100 g DW_{eq}, and by Torusdağ and colleagues (2021) in Damask rose (3747.16–5338.07 mg GAE/100 g DM), even if they used methanol:water (80:20) and acidified methanol (1% HCl) as extracting solutions respectively.

Regarding DPPH, Xiong and colleagues (2014) obtained a higher value for *Rosa chinensis* Jacq. (854 µmol TE/g DW), using 80% acetone as extracting solution.

It has to be noted that in this study acidified water was used to simulate extraction conditions for use in cosmetic and food. The higher literature values are probably due to the type of solvent used for extraction, since methanol and acetone are more efficient than water at extracting phenolics and antioxidants (Liu et al., 2009; Pratiwi and Nuraini, 2024).

3.1.2. *Effects of drying on TPC and DPPH*

Drying generally did not affect the TPC and DPPH in rose petals (Fig. 1).

The only exception was the increase in TPC in Damask rose after both drying methods.

Baibuch and colleagues (2023), who tested freeze-drying and hot air drying on different rose cultivars, also observed that TPC was not

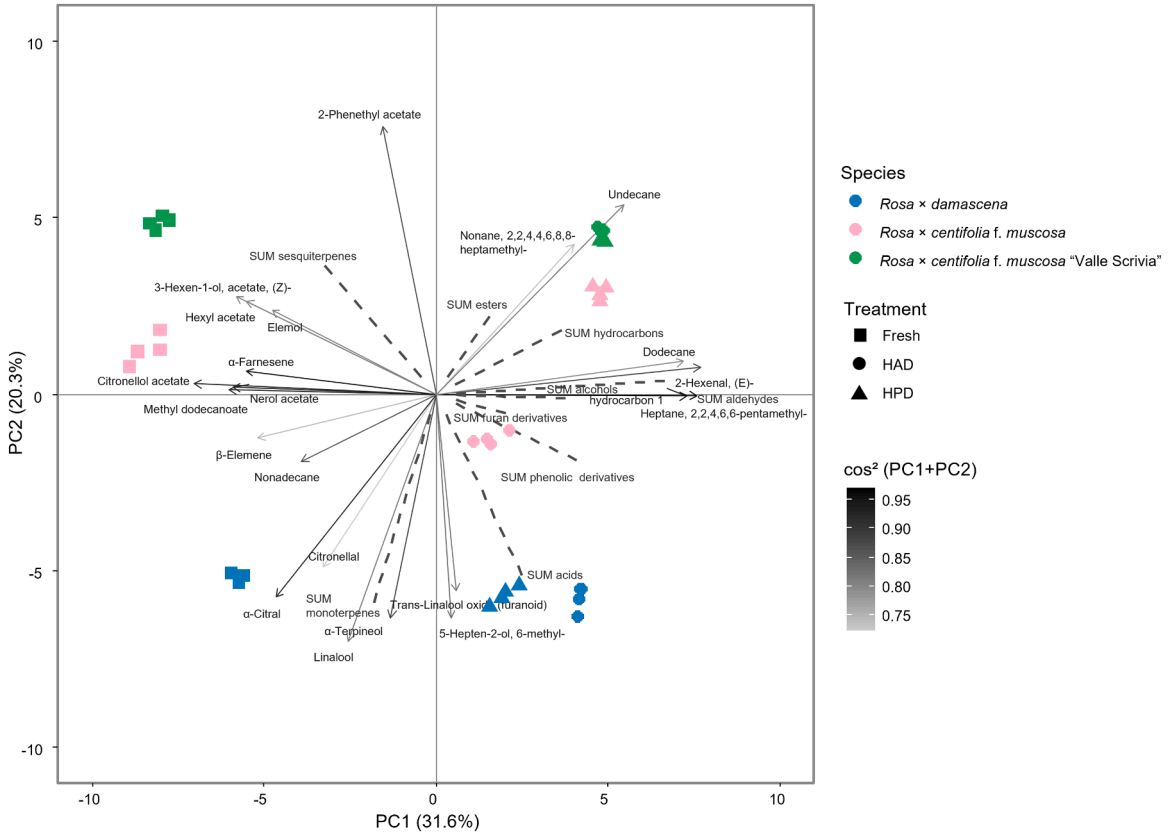


Fig. 2. PCA plot showing the relationships among the VOCs of the three fresh and dried (hot-air dried – HAD - and heat-pump dried - HPD) rose petals. The percentage variance explained by each axis is reported in brackets.

affected by the two drying methods in two out of four cultivars. They obtained higher TPC values, but it should be noted that they used different proportions of distilled water and absolute ethanol as extraction solvent.

3.2. Floral volatiles

A total of 106 VOCs were detected in the three fresh and dried rose flowers (Table S1; Figure S1). The PCA (Fig. 2) and heatmap (Fig. 3) performed on all VOC data (fresh and dried samples) allowed to visualize the distinct profiles of the three roses and the effect of the drying methods.

The PCA analysis explained 51.9% of the total variance on the first two axes (Fig. 2). The three roses and the three treatments were clearly separated based on their VOC compositions. Particularly, the first axis clearly separated the three roses, while the second axis differentiated the treatments (fresh, HAD and HPD).

The VOCs that differentiated the fresh roses the most were: α-citral and nonadecane mainly associated to the Damask rose, methyl dodecanoate, α-farnesene, and nerol acetate to the Moss rose, and 3-Hexen−1-ol, acetate, (*Z*)-, hexyl acetate, and elemol to the Valle Scrivia rose.

Drying modified the VOC profiles differently according to the species and method. Damask rose flowers dried using HAD were richer in total acids (acetic acid), while those dried using HPD were richer in *trans*-linalool oxid (furanoid). Moss rose flowers dried using HPD were richer in total hydrocarbons and furan derivatives, and lower in nonadecane and α-citral. Valle Scrivia rose flowers were less influenced by the drying method, resulting very similar and particularly rich in undecane and nonane, 2,2,4,4,6,8,8-heptamethyl-.

The heatmap also revealed distinct clusters, showing that the species vary in their VOCs levels (Fig. 3), consistently with the PCA results. Particularly, the Valle Scrivia clustered apart from the other two fresh roses, indicating a higher concentration of some terpenoids. The Damask rose showed higher concentrations of monoterpenes, namely α-terpinene, *cis*-verbenol, 3,9-epoxy−1-p-menthene, and lavandulol, as well as the benzenoid compound benzyl isopentanoate. The Moss rose showed higher concentrations of monoterpenes and esters.

Drying generally reduced the presence of these compounds in the respective roses. The drying methods especially differentiated the Moss rose; flowers dried using HPD were richer in hydrocarbons, while those dried using HAD were richer in monoterpenes. Conversely, Damask rose flowers dried using HAD were richer in hydrocarbons, while those dried using HPD were richer in monoterpenes.

Valle Scrivia rose flowers were less influenced by the drying method; the most evident difference was the formation of some esters and furan derivatives through HPD.

Based on these results, we examined the variation among all the identified VOCs, grouping them into categories and classes of compounds. This allowed to evaluate the differences in the composition of fresh flowers more in detail (see 3.2.1.) and to better evaluate the effect of drying (see 3.2.2.).

3.2.1. Fresh flowers

A total of 91 VOCs was detected in the three fresh roses, divided in fatty acids derivatives (5 compounds), acetate fermentation derivatives (7 compounds), benzenoids/phenylpropanoids (10 compounds), terpenoids (62 compounds), and other categories (7 compounds) (Tables 1–4).

Fatty acids derivatives included 3 classes: acids, alcohols, and aldehydes (Table 1); acetate fermentation derivatives included the class of esters, while benzenoids/phenylpropanoids, one of the main VOC groups giving flowers their scent (Nandhini et al., 2025), included the phenyl derivatives (Table 2); terpenoids, the most abundant VOC group in flowers (Nandhini et al., 2025), included two classes, namely monoterpenes and sesquiterpenes (Table 3); the two classes of furan derivatives and hydrocarbons were grouped in other categories (Table 4).

The rose with the highest VOC content resulted to be the Damask rose, with a total content of 90082.1 μg/kg (data not shown), constituted by 62 VOCs (5 fatty acids derivatives, 3 acetate fermentation derivatives, 8 benzenoids/phenylpropanoids, 40 terpenoids, and 6 belonging to other categories). The Moss rose (56917.1 μg/kg) and the Valle Scrivia rose (66696.2 μg/kg) showed similar lower contents (data not shown), constituted by 56 (2 fatty acids derivatives, 6 acetate fermentation derivatives, 4 benzenoids/phenylpropanoids, 40 terpenoids, and 4 belonging to other categories) and 58 (3 fatty acids derivatives, 5 acetate fermentation derivatives, 8 benzenoids/phenylpropanoids, 35 terpenoids, and 7 belonging to other categories) VOCs respectively. Therefore, each rose showed a peculiar aroma composition (Fig. 4). The three roses only shared 31 VOCs; the prevailing compound was the phenylethyl alcohol, a phenyl derivative representing 54–64% of the total VOC profile, followed by the monoterpene citronellol, representing 12–28% of the total VOC profile. These two compounds are known to be two of the main aroma compounds of rose products, together with geraniol (Martínez et al., 2020), which was found in high values in the Damask and Moss roses, but was not detected in the Valle Scrivia one.

It is interesting to note that both the Moss and the Valle Scrivia roses exhibited a large amount of the ester 2-phenethyl acetate (4 and 3% of the total VOCs detected respectively), while it was not detected in the Damask rose, probably being characteristic of the aroma profile of the centifolia moss species.

However, it is important to note that the fragrance of a rose is the result of a complex blend of numerous volatile compounds, some of which occur in trace concentrations only. The following paragraphs provide an in-depth description of the VOC classes, grouped by pathway.

3.2.1.1. Fatty acids derivatives. Regarding the fatty acids derivative pathway (Table 1), alcohols such as 3-hexen−1-ol, (*Z*)- (usually responsible for a green, grassy odour; Huang et al., 2022) and 1-hexanol (usually responsible for a fruity and alcoholic odour; Huang et al., 2022) were found in all three roses (the first being higher in the Moss and Valle Scrivia roses, while the second was similar in all three roses). The aldehyde 2-hexenal, (*E*)- (usually responsible for a sweet, almond and fruity odour; Huang et al., 2022) was only found in the Damask and Valle Scrivia roses in similar low amount, while acetic acid (usually responsible for a sour, vinegar odour; Huang et al., 2022) and the alcohol 5-hepten−2-ol, 6-methyl- were only found in the Damask rose. The absence of a compound may be ascribed to its low molecular weight, which makes it easy to volatilize, or to its variety specificity.

Overall, the Damask rose was the richest in fatty acids derivatives.

3.2.1.2. Acetate fermentation and Benzenoids/phenylpropanoids. In the acetate fermentation and benzenoids/phenylpropanoids pathways (Table 2), the esters found in all three roses were methyl acetate (higher values in the Valle Scrivia rose), and methyl dodecanoate (higher values in the Damask and Moss roses). The 3-hexen−1-ol, acetate, (*Z*)-, and hexyl acetate were found in both the Moss and Valle Scrivia roses (similar amount), while methyl decanoate was found in the Damask and Moss roses (higher values in the Damask one). The 2-hexen−1-ol, acetate, (*E*)- and phenylethyl alcohol, formate were only found in the Valle Scrivia rose. Methyl octanoate was only found in the Moss rose.

The 2-hexen−1-ol, acetate, (*E*)- probably originates from the reaction of an alcohol with acetic acid, or from fermentation. It may also be a variety-specific compound of the Valle Scrivia rose, similarly to phenylethyl alcohol, formate.

Methyl octanoate is usually responsible for a fruity, sweet odour (Huang et al., 2022; TGSC Information System, n.d.).

Overall, the Moss rose was the richest in VOCs from the acetate fermentation pathway, followed by the Valle Scrivia rose and lastly by the Damask one.

The phenyl derivatives (Table 2) found in all three roses were

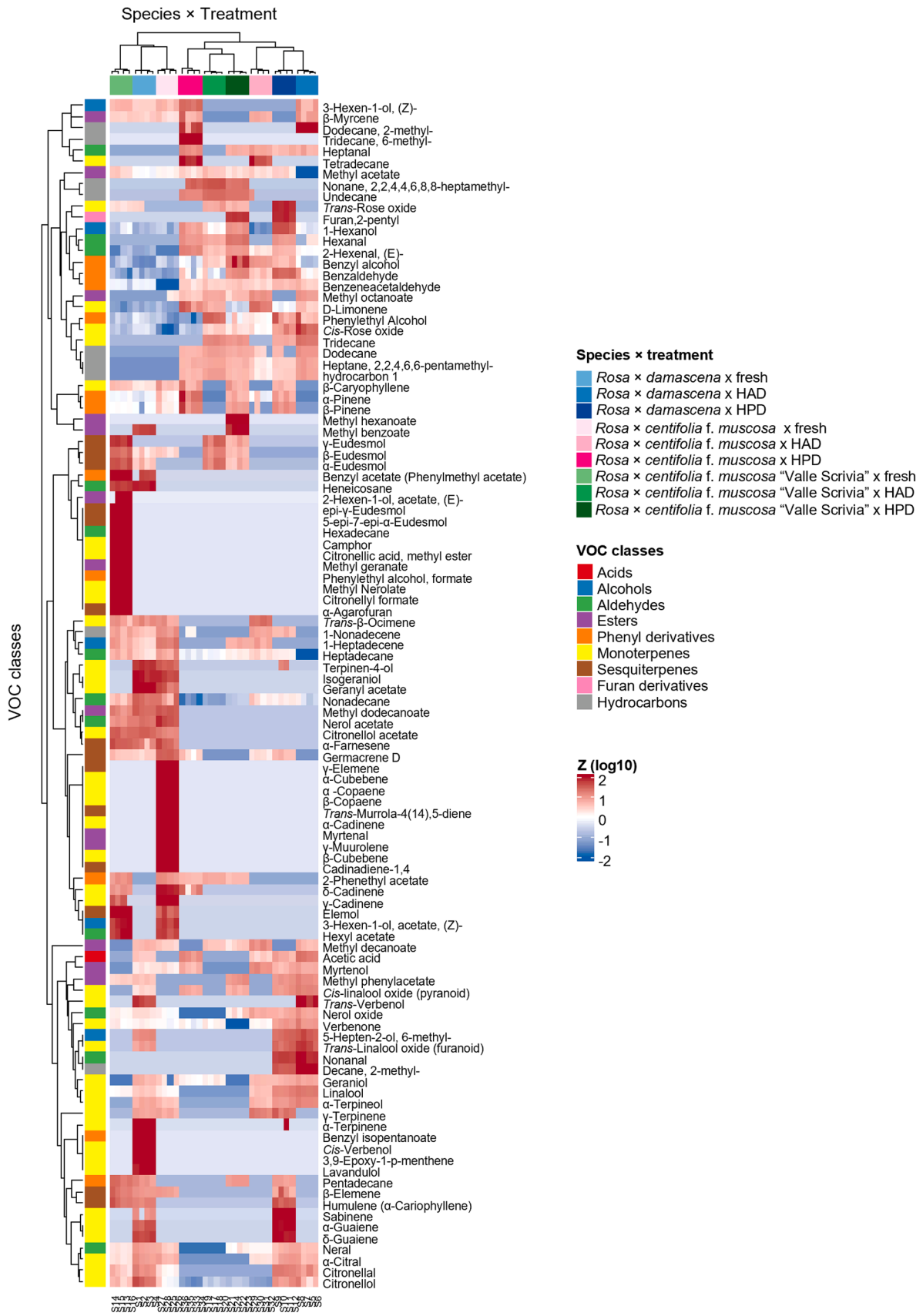


Fig. 3. Heatmap of VOCs in the three fresh and dried (hot-air dried – HAD - and heat-pump dried - HPD) rose petals.

Table 1
Volatile Organic Compounds (VOCs) of the fatty acid derivative pathway in fresh and dried rose petals of *R.* × *damascena*, *R.* × *centifolia muscosa*, and *R.* × *centifolia muscosa* "Valle Scrivia", and rose water. Asterisks indicate significant differences among fresh and dried flowers in the single species; the last significance column (*p* fresh flowers) refers to the significant differences among the three fresh roses only. Small case letters indicate differences among fresh, and HAD and HPD flowers, in the single species; capital letters indicate differences among the three fresh roses.

	Rosa × *damascena*						*Rosa* × *centifolia muscosa*						*Rosa* × *centifolia muscosa* "Valle Scrivia"						
VOC	**Fresh µg/kg**		**HAD µg/kg**		**HPD µg/kg**		**p**	**Fresh µg/kg**		**HAD µg/kg**		**HPD µg/kg**		**p**	**Fresh µg/kg**		**HAD µg/kg**		**HPD µg/kg**		**p**	**p (fresh flowers)**
Acetic acid	97.2 ±15.1	a	943.1 ±249.1	b	248.1 ±82.4	a	***	-		90.8 ±26.8	a	534.6 ±153.1	b	***	-		-		-		-	-
3-Hexen-1-ol, (*Z*)-	53.5 ±2.5	a A	183.2 ±119.9	b	-		*	110.4 ±26.5	a B	-		620 ±105.2	b	***	111 ±15.9	B	-		-		ns	**
1-Hexanol	340.3 ±55.9	a	739.1 ±203.7	a	5973.1 ±610.8	b	***	398.8 ±128.8	a	172.7 ±40.1	a	2854.2 ±453.8	b	***	585 ±244	a	1119 ±334.3	b	3113 ±207.2	c	***	ns
5-Hepten-2-ol, 6-methyl- §	102.9 ±13.3	a	321.7 ±93.7	c	212.1 ±29.1	b	**	-		-		-		-	-		-		-		-	-
Hexanal	-		94.1 ±108.7	a	3333.5 ±855.4	b	***	-		-		3703.8 ±1114.2		ns	-		1692.1 ±366.6	a	13472.6 ±1825	b	***	-
2-Hexenal, (*E*)-	8 ±4.8	a	331 ±110.6	a	4331.3 ±802.8	b	***	-		840.8 ±308.9	a	20464.8 ±4062.9	b	***	10.5 ±12.8	a	2915.7 ±731.8	b	10739.7 ±1454.5	c	***	-
Heptanal	-		250.9 ±95.1	b	196.9 ±67.2	a	ns	-		333.7 ±85.3	a	630.8 ±141.5	b	***	-		-		246.2 ±29		ns	-
Nonanal	-		418.6 ±84.6	b	276 ±21.2	a	***	-		-		-		-	-		-		-		-	-

Where "-" is found, it indicates that the compound was not detected. Data are presented as mean values. Significance is provided. *** = $p \leq 0.001$; ** = $p \leq 0.01$; * = $p \leq 0.05$; ns = not significant; §: tentative of identification, no pure standard available

benzaldehyde (similar amount), benzyl alcohol (higher values in the two *centifolia muscosa* roses), and phenylethyl alcohol (higher values in the Damask rose, followed by the Valle Scrivia, and lastly by the Moss one). Both the Damask and the Valle Scrivia roses contained benzyl acetate, in higher amounts in the second rose. They also contained methyl phenylacetate, in higher amounts in the first rose, and benzeneacetaldehyde, with similar amounts in both roses. 2-Phenethyl acetate was found in both the Moss and Valle Scrivia roses in similar amounts. Methyl benzoate and benzyl isopentanoate were only found in the Damask rose.

The 2-phenethyl acetate is probably formed through the reaction between acetic acid and phenyl ethyl alcohol or it may also be a variety-specific compound of some roses and can be found in the essential oil of the Damask rose (Jirovetz et al., 2005; Martínez et al., 2020). This compound has a typical floral rosy odour with sweet honey and tropical fruits notes (TGSC Information System, n.d.).

Benzaldehyde is a variety-specific compound of the essential oil of the Damask rose (Villa et al., 2022). Benzyl alcohol (almond odour) is known to have antimicrobial activity and, together with phenylethyl alcohol, they could be potentially used to increase the preservative action in cosmetic products; it was already found in the essential oils of the fresh petals of the Damask rose (Martínez et al., 2020; Villa et al., 2022). Phenylethyl alcohol is one of the main aroma compounds of rose products and was found in Narcea rose petals (Martínez et al., 2020). Benzyl acetate (phenylmethyl acetate) is a variety-specific compound of the Damask rose, and it derives from benzaldehyde, previously converted into benzyl alcohol, and then in benzyl acetate. It was reported in *Prunus mume*, *Clarkia breweri*, *Jasminum sambac*, and *Stephanotis floribunda* (Lv et al., 2024).

Methyl benzoate derives from the methylation of benzoic acid (Lv et al., 2024). It is a variety-specific compound of the damask rose, as well as benzyl isopentanoate.

Overall, the Damask rose was the richest in VOCs from the benzenoids/phenylpropanoids pathway, similarly to the Valle Scrivia rose.

3.2.1.3. Terpenoids. In the terpenoids pathway (Table 3), the monoterpenes found in similar amounts in all three roses were α-pinene, β-pinene, β-myrcene, D-limonene, *trans*-β-ocimene, verbenone. α-Pinene was already found in fresh *R. rugosa* flowers (Qiu et al., 2020) and in *R.* × *damascena* fresh petals essential oils, similarly to β-myrcene, verbenone, α-terpineol, and linalool (Villa et al., 2022). Conversely, differences were found among the three roses in linalool and citronellal (higher values in the two centifolia moss roses), in nerol oxide, citronellol, and neral (higher in the Damask rose), and in *cis*-rose oxide (highest value in the Damask rose, followed by the Valle Scrivia, and then by the Moss one). Nerol is another important monoterpene alcohol commonly found in rose species, but it was not detected in this study probably because in the column used (5% phenylsiloxane) it overlapped with citronellol; probably a more polar stationary phase would have allowed its separation. Similarly, also α-citral showed its highest value in the Damask rose, followed by the Moss one, and then by the Valle Scrivia one. Citronellol acetate was higher in the Damask and Valle Scrivia roses, while nerol acetate was higher in the Moss rose than in the other two roses. Linalool is known to be one of the most important compounds of the Damask rose, together with rose oxide, geraniol, and citronellal (Alizadeh and Fattahi, 2021; Jirovetz et al., 2005), in accordance with our findings. Linalool, *cis*-rose-oxide, citronellol, and geraniol contribute to a cut-grass aroma in roses (Jirovetz et al., 2005; Martínez et al., 2020). Particularly, citronellol gives a floral, intense rose-like, weak fruity aroma (Jirovetz et al., 2005). Neral has a rose-like, sweet, green aroma, while iso-geraniol has weak rose-like, green and herbaceous notes (Jirovetz et al., 2005).

Seven compounds were only found in the Damask and the Moss roses. Terpinen−4-ol, α-terpineol, geraniol, and geranyl acetate showed higher values in the Damask rose than in the Moss rose, while γ-terpinene, myrtenol and isogeraniol showed similar values in both roses.

Table 2
Volatile Organic Compounds (VOCs) of the acetate fermentation and benzenoids/phenylpropanoids pathways in fresh and dried rose petals of *R.* × *damascena, R.* × *centifolia muscosa,* and *R.* × *centifolia muscosa* "Valle Scrivia", and rose water. Asterisks indicate significant differences among fresh and dried flowers in the single species; the last significance column (*p* fresh flowers) refers to the significant differences among the three fresh roses only. Small case letters indicate differences among fresh and HAD and HPD flowers, in the single species; capital letters indicate differences among the three fresh roses.

		Rosa* × *damascena						***Rosa* × *centifolia muscosa***						***Rosa* × *centifolia muscosa* "Valle Scrivia"**						
Class	**VOC**	**Fresh µg/kg**		**HAD µg/kg**		**HPD µg/kg**	***p***	**Fresh µg/kg**		**HAD µg/kg**		**HPD µg/kg**	***p***	**Fresh µg/kg**		**HAD µg/kg**		**HPD µg/kg**	***p***	***p* (fresh flowers)**
Esters	Methyl acetate	231.4 ±44.2	a A	-		621 ±149.8	b ***	345.9 ±37	a A	569.9 ±151.1	b	575 ±139.8	b ***	703.5 ±174.5	b B	884.3 ±206.2	b	534 ±97	a *	***
	Methyl hexanoate	-		-		-	-	-		-		-	-	-		-		159.8 ±21.2	ns	-
	3-Hexen−1-ol, acetate, (*Z*)-	-		-		-	-	477.9 ±132.8		-		-	ns	689.9 ±236.5		-		-	ns	ns
	Hexyl acetate §	-		-		-	-	222.3 ±51.6		-		-	ns	435.7 ±232.7		-		-	ns	ns
	2-Hexen−1-ol, acetate, (*E*)- §	-		-		-	-	-		-		-	-	98.8 ±118.1		-		-	ns	-
	Methyl octanoate	-		4994.3 ±1140.4		-	ns	149.2 ±177.7	a	6668.6 ±1588.5	c	938.5 ±248.6	b ***	-		3063.4 ±236.4	b	1249.2 ±583.9	a ***	-
	Methyl decanoate	299.8 ±43.6	a B	313.8 ±115.5	b	-	***	159.9 ±42.4	a A	867 ±217.4	b	-	***	-		213.1 ±35.2		162.1 ±66.5	ns	**
	Methyl dodecanoate	78.9 ± 14.9	B	-		-	ns	96.4 ±9.2	B	-		-	ns	43.7 ±11.9	A	-		-	ns	***
Phenyl derivatives	Benzaldehyde	90.8 ±43.5	a	699.1 ±589.7	b	2947.4 ±173.9	c ***	58.3 ±13.8	a	802.8 ±156.1	c	412.4 ±298.8	b **	68 ±41	a	343.8 ±306.4	a	1831.5 ±198.8	b ***	ns
	Benzyl alcohol †	663.5 ±24.4	a A	1094.8 ±279.7	b	2255.7 ±160.4	c ***	1042.7 ±169	a B	2674.7 ±98.1	b	1262.6 ±256.9	a ***	974 ±176.1	a B	2003.1 ±166.7	b	3936.4 ±897	c ***	**
	Methyl benzoate	139.4 ±14.9		-		-	ns	-		-		-	-	-		-		233.1 ±54.2	ns	-
	Phenylethyl Alcohol †	48225.1 ±5061.7	a B	91265.9 ±25845.4	b	96289.3 ±18409.2	b **	35985.3 ±7474.3	a A	62598.8 ±4484.7	b	31724.6 ±5278	a ***	41701.3 ±4535.1	a AB	116035.7 ±4289	c	63106.2 ±13937.8	b ***	*
	2-Phenethyl acetate †	-		-		-	-	2236.9 ±766.2	b	-		578.3 ±99.4	a ***	2296.1 ±764.4	b	1040.3 ±102.3	a	563.5 ±78.9	a **	ns
	Phenylethyl alcohol, formate §	-		-		-	-	-		-		-	-	60.1 ±5		-		-	ns	-
	Benzyl acetate (Phenylmethyl acetate)	30.9 ±20.8	A	-		-	ns	-		-		-	-	102.9 ±16.7	B	-		-	ns	***
	Methyl phenylacetate	88.7 ±12.2	a B	373.8 ±90.7	b	279 ±36.2	c ***	-		-		-	-	59.2 ±9.6	a A	-		292.9 ±65.8	b ***	**
	Benzyl isopentanoate §	37.2 ±6		-		-	ns	-		-		-	-	-		-		-	-	-
	Benzeneacetaldehyde	374.2 ±42.4	a	2524.5 ±1161.6	b	3043.3 ±313.2	b ***	-		1536.1 ±322.6		1623.3 ±477.3	ns	294.2 ±142.7	a	1947.1 ±550.5	b	2266.1 ±367.6	b ***	ns

Where "-" is found, it indicates that the compound was not detected; where "†" is found, it indicates that the compound was also detected in constitutional waters (see Table 5). Data are presented as mean values. Significance is provided. *** = $p \leq 0.001$; ** = $p \leq 0.01$; * = $p \leq 0.05$; ns = not significant; §: tentative of identification, no pure standard available

Table 3
Volatile Organic Compounds (VOCs) of the terpenoid pathway in fresh and dried rose petals of *R. × damascena, R. × centifolia muscosa,* and *R. × centifolia muscosa* "Valle Scrivia", and rose water. Asterisks indicate significant differences among fresh and dried flowers in the single species; the last significance column (*p* fresh flowers) refers to the significant differences among the three fresh roses only. Small case letters indicate differences among fresh and HAD and HPD flowers, in the single species; capital letters indicate differences among the three fresh roses.

		Rosa × damascena						***Rosa × centifolia muscosa***						***Rosa × centifolia muscosa "Valle Scrivia"***						
Class	**VOC**	**Fresh µg/kg**		**HAD µg/kg**		**HPD µg/kg**		***p***	**Fresh µg/kg**		**HAD µg/kg**		**HPD µg/kg**	***p***	**Fresh µg/kg**		**HAD µg/kg**		**HPD µg/kg**		***p***	***p* (fresh flowers)**
Monoterpenes	α-Pinene	33.8 ±13.3	a	-		862.2 ±344.4	b	***	230.4 ±248.8		121.9 ±156.3		5894.1 ±6742	ns	54 ±17.5	a	-		602.2 ±201.2	b	***	ns
	Sabinene §	12.8 ±8.7	a	-		269.3 ±45.4	b	***	-		-		-	-	-		-		-		-	-
	β-Pinene	17.3 ±11.6	a	-		474.5 ±114.6	b	***	67 ±61.1		32.3 ±64.6		1234.4 ±1355.2	ns	28.4 ±2.7	a	-		338.5 ±51.5	b	***	ns
	β-Myrcene	104.8 ±17.6	a	351.5 ±141.8	b	-		***	93.9 ±43.3		247 ±39.8		510.4 ±592.3	ns	103.3 ±14.9		-		-		ns	ns
	α-Terpinene	16.8 ±2.2	b	-		12.7 ±25.5	a	***	-		-		-	-	-		-		-		-	-
	Limonene	30.7 ±3.9	a	140.3 ±19.6	c	70.2 ±6.3	b	***	29.8 ±8.4	a	289.6 ±32.6	b	276.9 ±78.9	b ***	23.7 ±3.9	a	176.1 ±15.2	c	48.4 ±7.9	b	***	ns
	trans-β-Ocimene	146.9 ±43.5		-		-		ns	107.7 ±53.2	a	282,5 ±46,2	b	-	***	102.4 ±50.9		-		-		ns	ns
	γ-Terpinene	47.4 ±3.5	a	-		145.1 ±46.7	b	***	41.8 ±10.2	a	108.1 ±22.4	b	-	***	-		-		-		-	ns
	Verbenone	183.3 ±20.6	a	1109.8 ±363.4	b	892.7 ±106.3	b	***	129 ±27.4		163 ±11.4		126.1 ±56.8	ns	181.4 ±47.9		190.5 ±46.7		-		ns	ns
	Linalool	646.1 ±96.5	a B	9333.2 ±1204.3	c	5945.6 ±989.9	b	***	154.9 ±57.7	a A	799.1 ±160.7	b	-	***	127.6 ±34.9	A	-		-		ns	**
	cis-Rose oxide	456.3 ±53.1	a C	3316 ±790.1	c	1931.1 ±373.6	b	***	114.1 ±33.2	a A	761.7 ±169.8	c	323.6 ±70.1	b ***	318.5 ±47.8	a B	1113.1 ±91.3	c	936.8 ±145.6	b	***	***
	trans-Rose oxide §	18.3 ±21.2	a A	-		1672.1 ±167.4	b	***	-		-		-	-	26.6 ±4.1	a B	117.7 ±38.5	c	75.5 ±11.4	b	**	*
	Camphor	-		-		-		-	-		-		-	-	69.5 ±7.5		-		-		ns	-
	Citronellal	221.6 ±61.9	a A	178.4 ±69.7	a	309 ±25.8	b	*	22.1 ±9.6	B	-		-	ns	60.8 ±35.7	B	-		-		ns	***
	Nerol oxide §	116.3 ±14	a B	441.5 ±118.2	b	324.7 ±65.6	b	***	56.8 ±21.2	a A	347 ±68.9	b	-	***	74.6 ±9.1	A	-		126.3 ±68.3		ns	***
	3,9-Epoxy−1-p-menthene §	102.1 ±5.9		-		-		ns	-		-		-	-	-		-		-		-	-
	cis-Verbenol	54.5 ±36.8		-		-		ns	-		-		-	-	-		-		-		-	-
	Terpinen−4-ol	354.7 ±44.8	b B	-		41.5 ±48.4	a	***	156.7 ±31.7	A	-		-	ns	-		-		-		-	***
	trans-Verbenol §	107.4 ±28	a	189.3 ±60.3	b	-		***	-		-		-	-	-		-		-		-	-
	α-Terpineol	118.5 ±19.9	a B	261.8 ±39.4	c	174.7 ±28.7	b	***	67.3 ±18.2	A	76.4 ±18.6		-	ns	-		-		-		-	**
	Myrtenal	-		-		-		-	29.7 ±9		-		-	ns	-		-		-		-	-
	Myrtenol	80.9 ±15	a	380.7 ±86.7	b	289.8 ±87.4	b	***	83.4 ±27	a	765.3 ±158.4	c	295 ±87.9	b ***	-		-		-		-	ns
	Citronellol † #	25660.8 ±4454.3	b B	13700.5 ±5628.2	a	16949.9 ±1886	a	**	6933 ±2538	b A	1997.2 ±149.9	a	1717.6 ±251	a **	11522.7 ±1823.2	b A	3474.3 ±434.6	a	3165.8 ±304.8	a	***	***
	Neral	1161.7 ±268.7	a B	635.7 ±267.2	c	791.9 ±225.9	ab	*	501.9 ±244.8	b A	137 ±1.9	a	-	**	214.5 ±19.5	A	-		172 ±75.9		ns	***

(*continued on next page*)

Table 3 (*continued*)

		Rosa × *damascena*						*Rosa* × *centifolia muscosa*						*Rosa* × *centifolia muscosa "Valle Scrivia"*					
	Isogeraniol §	128.7 ±23.1		-		-	ns	92.8 ±23.1		-		-		-		-		-	ns
	Geraniol †	3152.6 ±819.7	B	4619.6 ±881.9		3144.7 ±770.5	ns	838.1 ±714.7	a A	2304 ±287.4	b	338.6 ±89.3	a	***	-		468.8 ±130.2	-	ns	**
	Citronellic acid, methyl ester §	-		-		-	-	-		-		-		-	112.6 ±25		-	-	ns	-
	α-Citral	1359.2 ±452.6	C	719 ±413.3		1040.2 ±416.9	ns	733.3 ±333.9	b B	158.5 ±11.7	a	-		**	161.5 ±27.2	A	-	-	ns	***
	Citronellyl formate §	-		-		-	-	-		-		-		-	55.3 ±6.9		-	-	ns	-
	Methyl Nerolate §	-		-		-	-	-		-		-		-	160 ±42.4		-	-	ns	-
	Methyl geranate	-		-		-	-	-		-		-		-	735.8 ±199.3		-	-	ns	-
	Citronellol acetate	445.1 ±48	B	-		-	ns	194.3 ±41.8	A	-		-		ns	437.5 ±100.8	B	-	-	ns	***
	Nerol acetate	51.3 ±7.8	A	-		-	ns	107.8 ±39	B	-		-		ns	32.9 ±7.4	A	-	-	ns	**
	Geranyl acetate	880.8 ±336.9	B	-		-	ns	177.8 ±105.1	A	-		-		ns	-		-	-	-	**
	cis-Linalool oxide (pyranoid) † §	48.5 ±9.6	a	418 ±53.7	b	259.1 ±56	c	***	-		-		162.7 ±29.7	ns	-		-	141 ±25.9	ns	-
	trans-Linalool oxide (furanoid) §	26 ±4.7	a	118.1 ±36.4	b	68.3 ±11.5	c	***	-		-		-	-	-		-	-	-	-
Sesquiterpenes	α-Cubebene	-		-		-	-	51.5 ±6.8		-		-		ns	-		-	-	-	-
	α-Copaene	-		-		-	-	77 ±7.3		-		-		ns	-		-	-	-	-
	Lavandulol	35.6 ±16.3		-		-	ns	-		-		-		-	-		-	-	-	-
	β-Cubebene	-		-		-	-	39.6 ±5.8		-		-		ns	-		-	-	-	-
	β-Elemene	41.2 ±2.7	A	-		57.2 ±51.6	ns	36.2 ±5.2	A	-		-		ns	80.5 ±23.9	B	-	-	ns	**
	β-Caryophyllene	69.9 ±7.5	a	-		217.2 ±56.9	b	***	268.4 ±216.2		-		537.2 ±497.9	ns	187.1 ±34.2	a	-	333.9 ±154	b	**	ns
	β-Copaene	-		-		-	-	60.3 ±8.7		-		-		ns	-		-	-	-	-
	trans-Muurola−4 (14),5-diene §	-		-		-	-	38 ±5.7		-		-		ns	-		-	-	-	-
	α-Guaiene	57.3 ±12	a	-		162.1 ±34.6	b	***	-		-		-	-	-		-	-	-	-
	Humulene (α-Caryophyllene)	46.2 ±4.5	a A	-		90.6 ±18	b	***	-		-		-	-	73.9 ±26.9	B	-	-	ns	***
	γ-Muurolene	-		-		-	-	44.5 ±6.1		-		-		ns	-		-	-	-	-
	Germacrene D	63.8 ±12.1	a A	-		107.3 ±23.1	b	***	710.7 ±76.1	b B	44.6 ± 8.8	a	63.3 ± 40.1	a	***	87.8 ±22.8	A	-	-	ns	***
	α-Agarofuran	-		-		-	-	-		-		-		-	35.3 ±2		-	-	ns	-
	γ-Elemene	-		-		-	-	111 ±6.5		-		-		ns	-		-	-	-	-
	δ-Guaiene	52.8 ±6.3	a	-		81.2 ±5.5	b	***	-		-		-	-	-		-	-	-	-

(*continued on next page*)

Table 3 (*continued*)

	Rosa × *damascena*				*Rosa* × *centifolia muscosa*				*Rosa* × *centifolia muscosa "Valle Scrivia"*				
α-Farnesene	21.4 ±10.7	A	-	***	38.8 ±14.8	AB	-	ns	42.4 ±6.5	B	-	-	ns	*
γ-Cadinene	-		-		52.5 ±8.8	B	-	ns	11.9 ±8.5	A	-	-	ns	***
δ-Cadinene §	-		-	-	199.5 ±14.4	b B	-	42.1 ± 31.8 a	30.9 ±4.7	*** A	-	-	ns	***
Cadinadiene−1,4 §	-		-	-	23.3 ±4		-	ns	-		-	-	-	-
α-Cadinene	-		-	-	24.8 ±6.4		-	ns	-		-	-	-	-
Elemol	-		-	-	44.7 ±16.6	A	-	ns	119.5 ±16.7	B	-	-	ns	***
5-epi−7-epi-α-Eudesmol §	-		-	-	-		-	-	19.4 ±3.7		-	-	ns	-
epi-γ-Eudesmol §	-		-	-	-		-	-	20.9 ±2.9		-	-	ns	-
γ-Eudesmol	-		-	-	-		-	-	238.1 ±41.5	c	94.2 ±30.2	b 25.2 ±9.5	a ***	-
B-Eudesmol	40.6 ±23.6	A	-	-	43.3 ±12.6	A	-	ns	480.8 ±84.5	c B	264 ±56	b 76.6 ±15.8	a ***	***
α-Eudesmol	31.9 ±16.2	A	-	-	-	ns	-	-	331.6 ±61.3	c B	162.5 ±56.5	b 38.7 ±18.9	a ***	***

Where "-" is found, it indicates that the compound was not detected; where "↓" is found, it indicates that the compound was also detected in constitutional waters (see Table 5); where "#" is found, it indicates that the correct isomer was not identified. Data are presented as mean values. Significance is provided. *** = $p \leq 0.001$; ** = $p \leq 0.01$; * = $p \leq 0.05$; ns = not significant; §: tentative of identification, no pure standard available.

Terpinen−4-ol is a variety-specific compound already found in the Damask rose essential oil, giving a spicy, woody-earthy, nutmeg and lilac notes aroma (Jirovetz et al., 2005).

Conversely, *trans*-rose oxide was only found in the Damask and in the Valle Scrivia roses, being higher in the first one. *Trans*-rose-oxide is an important compound for rose scent (Jirovetz et al., 2005). It is a variety-specific compound, and is present in traces in the Damask rose.

Damask rose variety-specific compounds were: sabinene, α-terpinene, 3,9-epoxy−1-p-menthene, *cis*-verbenol, *trans*-verbenol, *cis*-linalool oxide (pyranoid), and *trans*-linalool oxide (furanoid). α-Terpinene, together with limonene, *cis*-β-ocimene, and α-citral, is an important compound in cosmetic and rose essential oil production (Alizadeh and Fattahi, 2021; Jirovetz et al., 2005; Martínez et al., 2020). *Cis*-linalool oxide (pyranoid) has sweet-woody, floral-woody-earthy side-notes, while *trans*-linalool oxide (furanoid) has a more powerful sweet-woody, floral aroma (Jirovetz et al., 2005).

Moss rose variety-specific compound was myrtenal.

Valle Scrivia rose variety-specific compounds were: camphor, citronellic acid, methyl ester, citronellyl formate, methyl nerolate, and methyl geranate. Citronellyl formate, similarly to geranyl acetate, (rose and lavender-like, sweet-fruity aroma - Jirovetz et al., 2005) have been known to harmonize the scent of rose essential oils (Martínez et al., 2020).

Overall, the Damask rose was the richest in monoterpenes, while the other two roses showed lower values.

The sesquiterpene found in similar amounts in all three roses was the β-caryophyllene (terpene-odour, woody, spicy aroma). Conversely, differences were found among the three roses in β-elemene and β-eudesmol (higher values in the Valle Scrivia rose than in the other two ones), germacrene D (higher value in the Moss rose than in the other two ones), and α-farnesene (highest value in the Valle Scrivia rose, similarly followed by the Moss rose and lastly by the Damask rose). α-Farnesene was also found in fresh *R. rugosa* flowers (Qiu et al., 2020).

Two VOCs were only found in the Valle Scrivia and Damask roses: humulene (α-caryophyllene; with fresh-green, weak woody odour - Jirovetz et al., 2005) and α-eudesmol (higher values in the Valle Scrivia rose).

Three VOCs were only found in the two *centifolia muscosa* roses: γ-cadinene and δ-cadinene (higher values in the Moss rose), and elemol (highest value in the Valle Scrivia rose).

Rosa × *damascena* variety-specific compounds were: lavandulol, α-guaiene, and δ-guaiene. β-Caryophyllene was already found in the essential oil of the Damask rose, as well as humulene (α-caryophyllene), germacrene D, α-cadinene, γ-cadinene, δ-cadinene, elemol, epi-γ-eudesmol, α-eudesmol, β-eudesmol, and γ-eudesmol (Alizadeh and Fattahi, 2021; Villa et al., 2022).

Rosa × *centifolia muscosa* variety-specific compounds were: α-cubebene, α-copaene, β-cubebene, β-copaene, *trans*-murrola−4(14),5-diene, γ-muurolene, γ-elemene, cadinadiene−1,4, and α-cadinene. α-Cubebene has an herbal-woody aroma (Jirovetz et al., 2005).

Rosa × *centifolia muscosa* "Valle Scrivia" variety-specific compounds were: α-agarofuran, 5-epi−7-epi-α-eudesmol (many isomers of eudesmol), epi-γ-eudesmol, and γ-eudesmol.

Overall, the two centifolia moss roses were the richest in sesquiterpenes.

3.2.1.4. Other categories. Regarding the other categories of compounds (Table 4), the hydrocarbons 1-heptadecene and 1-nonadecene were found in all three roses (highest values in the Moss rose, followed by the Valle Scrivia and lastly by the Damask rose). 1-Nonadecene was reported to be among the main compounds of the Damask rose (Alizadeh and Fattahi, 2021). Similarly, higher values were observed for heptadecane in the two centifolia moss roses than in the Damask rose. Heptadecane was already observed in the essential oil of the Damask rose and has a weak fatty aroma (Jirovetz et al., 2005). Conversely, higher

Table 4
Volatile Organic Compounds (VOCs) of other categories in fresh and dried rose petals of *R.* × *damascena, R.* × *centifolia muscosa,* and *R.* × *centifolia muscosa* "Valle Scrivia", and rose water. Asterisks indicate significant differences among fresh and dried flowers in the single species; the last significance column (*p* fresh flowers) refers to the significant differences among the three fresh roses only. Small case letters indicate differences among fresh and HAD and HPD flowers, in the single species; capital letters indicate differences among the three fresh roses.

		Rosa* × *damascena							***Rosa* × *centifolia muscosa***							***Rosa* × *centifolia muscosa* "Valle Scrivia"**								
Class	**VOC**	**Fresh µg/kg**		**HAD µg/kg**		**HPD µg/kg**		***p***	**Fresh µg/kg**		**HAD µg/kg**		**HPD µg/kg**		***p***	**Fresh µg/kg**		**HAD µg/kg**		**HPD µg/kg**		***p***	***p* (fresh flowers)**
Furan derivatives	Furan,2-pentyl	-		-		631.5 ±96.6		ns	-		-		-		-	-		-		540.7 ±31.3		ns	-
Hydrocarbons	Heptane, 2,2,4,6,6-pentamethyl- §	-		1160.7 ±223.2	b	292.1 ±18.1	a	***	-		190.3 ±144.4	a	724.5 ±155.3	b	***	-		1027.3 ±115.9	b	634.6 ±86.5	a	***	-
	Hydrocarbon n.1 §	-		746.4 ±135.5	b	209 ±20.9	a	***	-		123.2 ±72.4	a	390.7 ±42.1	b	***	-		781.8 ±66.3	b	380 ±42	a	***	-
	Decane, 2-methyl- §	-		151.6 ±27.4	b	51.1 ±3.6	a	***	-		-		-		-	-		-		-		-	-
	Nonane, 2,2,4,4,6,8,8-heptamethyl- §	-		-		-		-	-		-		122.1 ±83.2		ns	-		225.8 ±17.8	b	118.3 ±9.8	a	***	-
	Tridecane, 6-methyl- §	-		-		-		-	-		-		401.2 ±56		ns	-		-		-		-	-
	Undecane	-		-		-		-	-		214.3 ±428.5	a	1314.2 ±134.3	b	***	-		3493 ±273	b	2566.9 ±165.5	a	***	-
	Dodecane	-		1933.6 ±266.9	b	301.7 ±349	a	***	-		339.5 ±364.4		622.3 ±72.3		ns	-		1400.5 ±152.3	b	964.7 ±105	a	***	-
	Dodecane, 2-methyl- §	-		383.7 ±16.3		-		ns	-		-		142.6 ±85.8		ns	-		-		-		-	-
	Tridecane	-		719.3 ±111.4	b	165.4 ±16.7	a	***	-		-		-		-	-		428.3 ±46.4	b	287.3 ±40.6	a	***	-
	Pentadecane	96.9 ±31	A	-		71.8 ±7.7		ns	-		-		-		-	207.4 ±46.5	b B	-		83.8 ±8.5	a	***	**
	Hexadecane	-		-		-		-	-		-		-		-	17,3 ±6		-		-		ns	-
	Tetradecane	-		-		-		-	-		144.2 ±105		199.7 ±58.1		ns	-		-		-		-	-
	1-Heptadecene §	25.5 ±6.8	A	-		-		ns	168.9 ±34.8	b C	66.7 ±16.4	a	-		***	71.1 ±25	B	-		56.7 ±7.2		ns	***
	Heptadecane	169.5 ±38.4	b A	-		121.4 ±7.7	a	***	462 ±162.6	b B	179.1 ±35	a	55.6 ±12.3	a	***	343.2 ±64.1	b B	74.7 ±16.3	a	123.5 ±9.3	a	***	**
	1-Nonadecene §	143.6 ±47.8	a A	-		181.1 ±50.2	a	ns	489.7 ±107.8	c C	321.5 ±53.7	b	18.2 ±21	a	***	298.6 ±98.2	B	-		-		ns	***
	Nonadecane	2243.1 ±278.4	b B	317.2 ±150.6	a	560 ±41.5	a	**	1684.7 ±697.9	b B	656.3 ±182.9	a	68.6 ±22.8	a	**	961.2 ±198.7	b A	110.7 ±12.4	a	204.1 ±19.6	a	***	**
	Heneicosane	295.9 ±24.4		-		-		ns	-		-		-		-	200 ±24.1		-		-		ns	ns

Where "-" is found, it indicates that the compound was not detected. Data are presented as mean values. Significance is provided. *** = $p \leq 0.001$; ** = $p \leq 0.01$; * = $p \leq 0.05$; ns = not significant; §: tentative of identification, no pure standard available

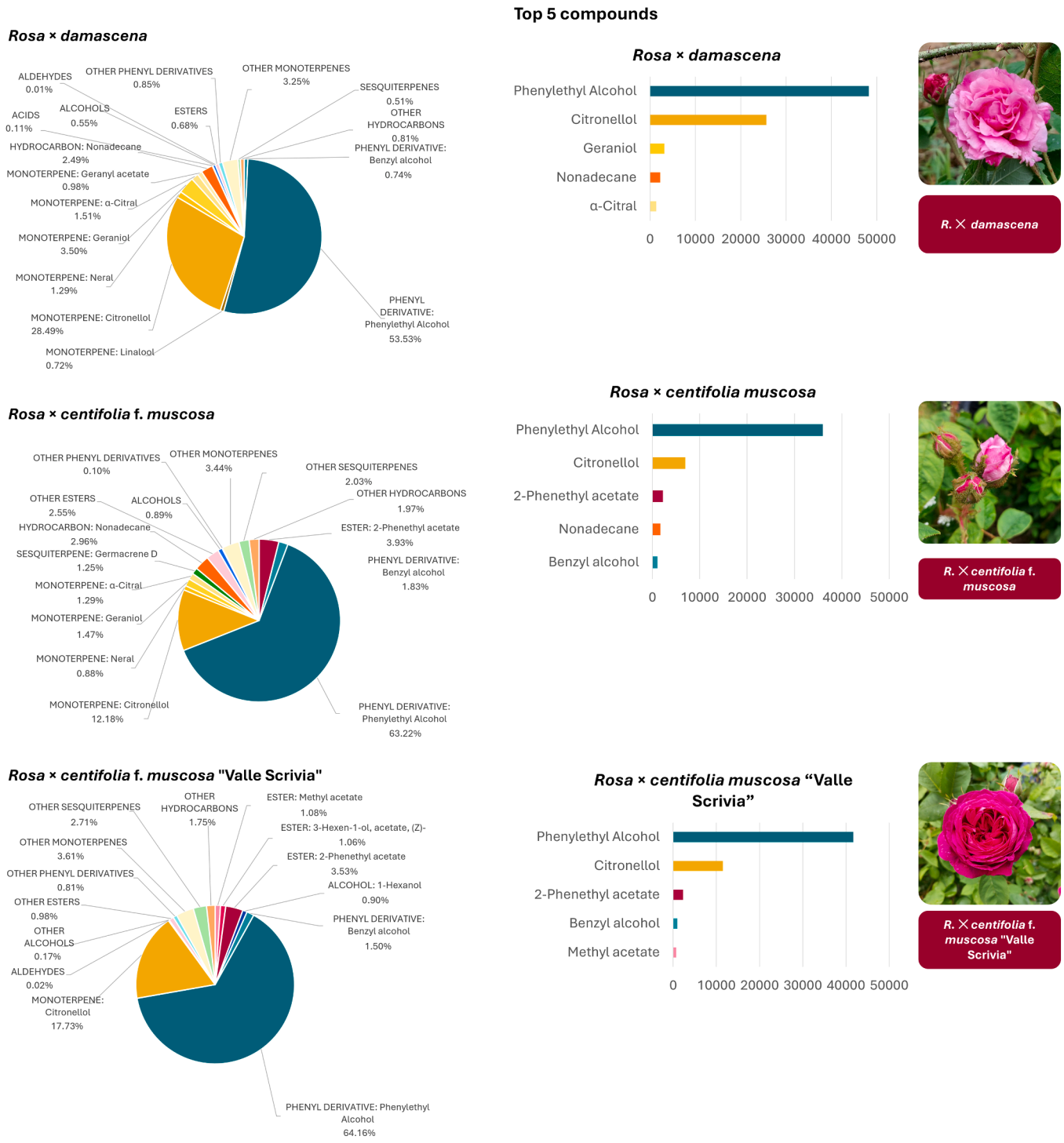


Fig. 4. VOC profile of the three fresh roses. Compounds with a concentration > 500 μg/kg were individually specified, written in lower case, preceded by their class (capital letters). Compounds with a concentration < 500 μg/kg were summed up and presented as a class, written in CAPITAL LETTERS. The five most abundant compounds in each rose were better illustrated in the histograms on the right.

values were observed for nonadecane in the Damask and in the Moss roses than in the Valle Scrivia one. Nonadecane is known to reduce the quality of rose essential oil, as well as heneicosane (Martínez et al., 2020).

Two VOCs were only found in the Damask and the Valle Scrivia roses: pentadecane (highest value in the Valle Scrivia rose) and heneicosane (similar values in both roses).

Hexadecane was only found in the Valle Scrivia rose; it may be a variety-specific compound of the Valle Scrivia rose, or resulting from exogenous pollution.

Overall, the three roses showed similar hydrocarbons contents.

3.2.2. *Effects of drying on volatile compounds*

Overall, the drying methods quantitatively affected the VOCs profile of the three roses.

A total of 71 VOCs was detected in the three HAD and HPD rose petals, divided in fatty acids derivatives (8 compounds), acetate fermentation derivatives (5 compounds), benzenoids/phenylpropanoids

(8 compounds), terpenoids (34 compounds), and other categories (16 compounds) (Tables 1–4).

Some VOCs increased or decreased during drying; other VOCs, which were present in the fresh petals, disappeared after drying; other VOCs, which were not present in the fresh petals, formed during the drying process (Fig. 5).

In general, HAD and HPD similarly increased the total VOCs in the Damask rose and in the Moss rose, while HAD led to a higher increase than HPD in the Valle Scrivia rose.

The majority of the VOCs content in the Damask rose (an average of 55.8% of the total relative content in fresh petals among all VOCs present) was represented by total phenyl derivatives, in agreement with literature (Martínez et al., 2020; Nedeltcheva-Antonova et al., 2017). These aromatic metabolites (5 compounds among all the present volatiles) increased in HAD (72.2%) and HPD (70.7%). These compounds showed a similar behaviour in the Valle Scrivia rose (an average of 74.8% of the total content of all present volatiles in fresh samples), increasing during HAD (93.2%) and HPD (87.0%). Conversely, in the Moss rose, the majority of the VOCs was represented by the total monoterpenoids (an average of 49.2% among all the present volatiles). These VOCs decreased in HAD (33.9%) and HPD (18.2%). The total phenyl derivatives were instead the second most abundant VOC class (an average of 28.6% among all the present volatiles), in agreement with literature (Martínez et al., 2020; Nedeltcheva-Antonova et al., 2017), increasing in HAD (55.8%) and HPD (73.2%).

In general, HPD preserved more hydrocarbons (10 compounds) than HAD (8 compounds).

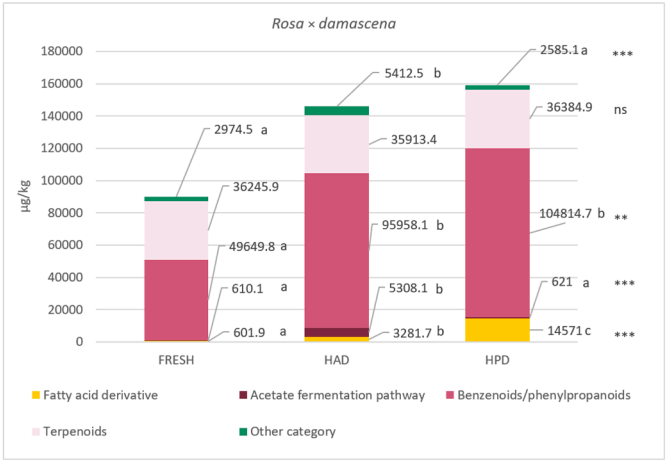
In particular, HPD was preferable for Damask rose because it increased sesquiterpenes, and similarly preserved the total monoterpenes. The lower drying temperature likely played (30°C vs. 60°C) a positive role in the lower volatilization and/or the greater thermal stability of enzymes.

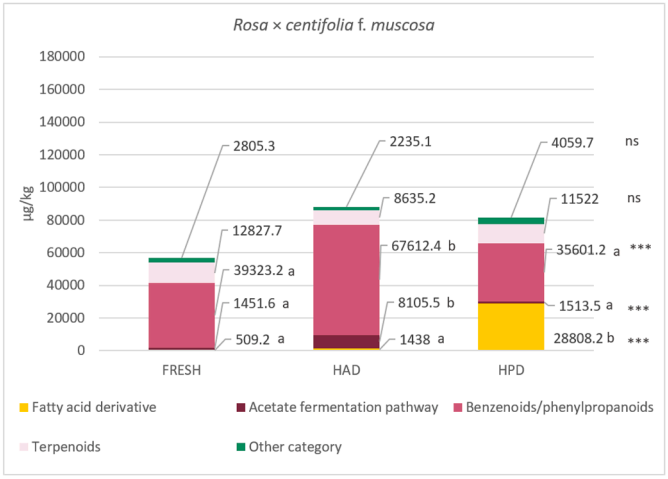
In the Valle Scrivia rose, HPD also preserved more some volatile monoterpenes, such as α- and β-pinene, and nerol oxide than HAD. A new VOC formed, i.e., *cis*-linalool oxide (pyranoid), which was not present nor in the fresh and the HAD petals, suggesting the hydrolysis of the linked monoterpene or the oxidation of linalool.

Instead, HAD better preserved certain monoterpenes in the two moss roses, namely *trans*-β-ocimene, γ-terpinene, linalool, *cis*-rose oxide, nerol oxide, myrtenol, and geraniol in the Moss rose, while D-limonene, *cis*-rose oxide, *trans*-rose oxide, and geraniol in the Valle Scrivia rose, although no differences were found in the total monoterpenes.

Citronellol, an important aromatic monoterpene found in all three roses, was present in a similar lower content after both drying methods, suggesting similar volatilization in both HAD and HPD drying.

3.2.2.1. Fatty acids derivatives. Regardless of the method used, no VOCs of this pathway decreased or disappeared; conversely, drying had a positive effect on the concentration of 1-hexanol, since it increased, while hexanal and heptanal formed. Similarly, 2-hexenal, (*E*)- generally largely increased in the Damask and Valle Scrivia roses, and it formed in the Moss rose.





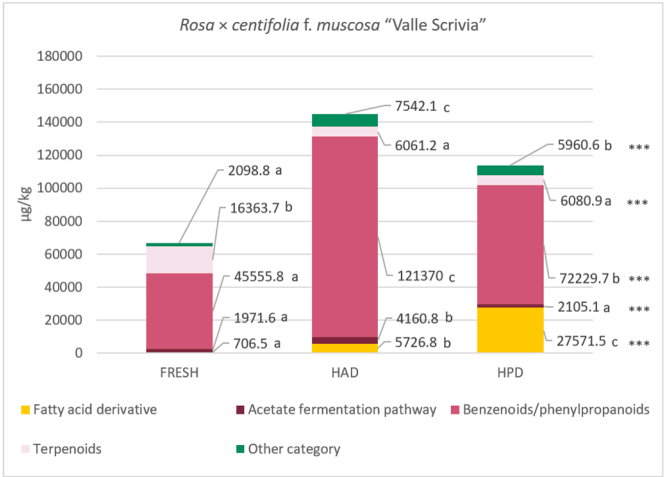


Fig. 5. Distribution of the VOC pathways in fresh, HAD and HPD, in *R.* × *damascena, R.* × *centifolia muscosa*, and *R.* × *centifolia muscosa* "Valle Scrivia". Asterisks indicate significant differences among fresh and dried flowers in the single species. Small case letters indicate differences among fresh, and HAD and HPD flowers, in the single species. Significance is provided. *** = $p \leq 0.001$; ** = $p \leq 0.01$; ns = not significant.

Heat-pump drying generally increased or formed the alcohols and aldehydes in all three roses more than HAD. In the Moss rose, HPD also formed the acids, while HAD increased them in the Damask rose.

More specific differences between each rose can be seen in detail in the Table 1.

3.2.2.2. Acetate fermentation and Benzenoids/phenylpropanoids. Regardless of the drying method used, methyl dodecanoate disappeared after drying, as well as benzyl acetate, 3-hexen−1-ol, acetate, (*Z*)-, and hexyl acetate in all three roses. In Damask rose, also methyl benzoate and benzyl isopentanoate disappeared, suggesting that they had evaporated at higher temperatures following the drying processes. Conversely, benzaldehyde, benzyl alcohol, and phenylethyl alcohol increased in all three roses.

Methyl decanoate increased in the Damask and Moss roses, and it formed in the Valle Scrivia one, similarly to benzeneacetaldehyde, which however formed in the Moss rose.

More in detail, regarding the Damask rose, the total concentration of phenyl derivatives was similar in both drying methods, and twice that of fresh petals. HPD particularly concentrated benzyl alcohol and benzaldehyde, up to two to four times more than HAD. Conversely, HAD increased the phenyl derivatives the most in the moss roses.

The total esters only increased after HAD in the Valle Scrivia rose and formed in the Damask and Moss ones. The more abundant methyl ester was represented by methyl octanoate, which was only present in HAD. This suggests that artefact production under stress conditions is more likely to result in esterification, which probably has a positive effect on the odour quality. Among acetate esters, methyl acetate was found only in fresh and cold dried petals, probably because of a soft drying method.

More specific differences between each rose can be seen in detail in Table 2.

3.2.2.3. Terpenoids. Regardless of the drying method used, several terpenoids disappeared (citronellol acetate, nerol acetate, α-farnesene, isogeraniol, geranyl acetate, γ-cadinene, and elemol), or decreased (citronellol) in all three roses (Table 3). β-Eudesmol decreased in the Valle Scrivia rose and disappeared in the other two roses. Drying conversely increased some other terpenoids, such as limonene and *cis*-rose oxide increased in all three roses.

The drying methods affected the content of the other terpenoids.

β-Elemene and citronellal generally disappeared, but they were preserved through HPD in the Damask rose. Conversely, *trans*-β-ocimene generally disappeared, but it increased through HAD in the Moss rose.

β-Caryophyllene, α-pinene and β-pinene disappeared after HAD, while it increased in the Damask and Valle Scrivia roses after HPD, and maintained its content in the Moss one.

Myrtenol and *cis*-linalool oxide (pyranoid) increased in the Damask rose and formed through HPD in the other two roses.

The total monoterpenes did not change in both Damask and Moss roses. This latter rose showed a higher number of monoterpenes through HAD (16 compounds) than HPD (10 compounds), with geraniol, myrtenol, α-citral and linalool being the most prevalent.

The total sesquiterpenes disappeared through HAD, while they increased through HPD in the Damask rose; they decreased after both drying processes in the Moss rose.

In the Valle Scrivia rose, the total amount of monoterpenes and sesquiterpenes decreased after drying. In general, HPD preserved a larger number of terpenes (13 compounds) than HAD (9 compounds). HPD petals showed a decrease in the amount of all volatile monoterpenoids, with the formation of a new VOC, *cis*-linalool oxide (pyranoid).

More specific differences between each rose can be seen in detail in the Table 3.

3.2.2.4. Other categories. Regardless of the method used, it is interesting to note the formation of new compounds, such as various hydrocarbons after drying (Table 4): heptane,2,2,4,6,6-pentamethyl-, hydrocarbon n.1, and dodecane formed in all three roses; nonane,2,2,4,4,6,8,8-heptamethyl- and undecane formed in the two moss roses; furan,2-pentyl and tridecane formed in the Damask and Valle Scrivia roses.

A new furan derivative was also produced by Maillard reactions, i.e., the furan,2-pentyl, in the Damask and Valle Scrivia roses through HPD. Adverse Maillard products, such as the toxic furan, were not found in any of the three dried roses. These findings support the effectiveness of both drying methods in ensuring the safety of rose products.

Conversely, other compounds decreased or disappeared after drying (Table 4). Nonadecane decreased in all three roses; heptadecane generally decreased and disappeared through HAD in the Damask rose; heneicosane disappeared after drying. This was probably caused by lipid oxidation forming some linear aldehydes (which increased).

Regarding the Damask rose, HAD increased the total hydrocarbons.

Regarding the Moss rose, no changes were observed in total hydrocarbons after both drying processes.

In the Valle Scrivia rose, the total hydrocarbons increased after both drying processes, especially after HAD.

More specific differences between each rose can be seen in detail in the Table 4.

From an application perspective, an "aromatic quality preservation" (AQP) index was calculated by dividing the sum of the concentrations (μg/kg) of the key markers (phenylethyl alcohol, citronellol, geraniol) in the dried flowers by the sum of the concentrations of the same key markers in fresh flowers (77038.5 μg/kg, 43756.4 μg/kg, and 53224 μg/kg for the Damask, Moss and Valle Scrivia roses, respectively). These key markers were chosen according to their sensory importance (Jirovetz et al., 2005).

Heat-pump drying better preserved the Damask rose quality (AQP_{HPD} =1.51) than HAD (AQP_{HAD} = 1.42).

Hot-air drying better preserved the quality of Moss (AQP_{HAD} = 1.53) and Valle Scrivia (AQP_{HAD} = 2.25) roses than HPD (AQP_{HPD} =0.77 and AQP_{HPD} =1.24, respectively). Particularly, it has to be noted that the Valle Scrivia rose only presented geraniol in HAD flowers.

3.2.3. Evaluation of condensed rose water

The humid drying air of the HPD system was cooled to extract the moisture, giving the condensed water (Geng et al., 2020).

The VOCs content (μg/kg) of condensed waters obtained from the

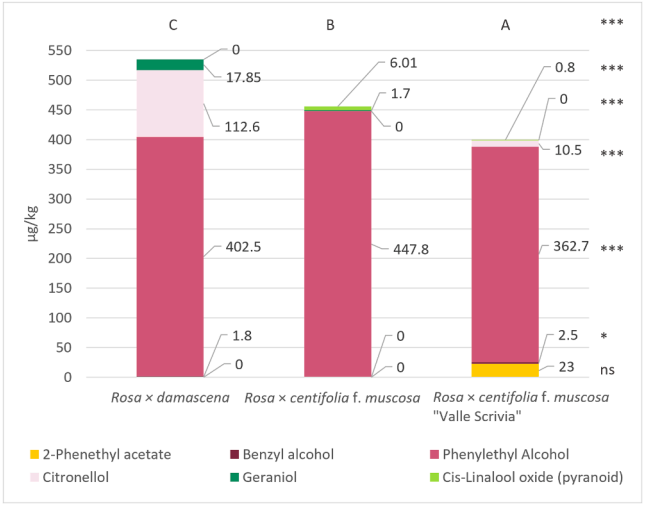


Fig. 6. Distribution of the condensed water VOCs in *R.* × *damascena, R.* × *centifolia muscosa*, and *R.* × *centifolia muscosa* "Valle Scrivia". Capital letters indicate differences among the three roses. Significance is provided. *** = $p \leq 0.001$.

three studied roses is reported in Fig. 6.

In the Damask rose condensed water four VOCs were identified: benzyl alcohol, phenylethyl alcohol, citronellol, and geraniol. The total VOCs concentration was more than 100 times lower than in the fresh rose samples. In the Moss rose condensed water three VOCs were identified: phenylethyl alcohol, geraniol and *cis*-linalool oxide (pyranoid). The total VOCs concentration was more than 200 less concentrated than its respective HPD petals. In the Valle Scrivia rose condensed water five VOCs were identified: benzyl alcohol, phenylethyl alcohol, 2-phenethyl acetate, citronellol, and *cis*-linalool oxide (pyranoid). The total VOCs concentration was almost 300 times less concentrated than its respective HPD petals.

The highest total VOC content was obtained in the Damask rose (534.8 μg/kg), followed by the Moss one (455.5 μg/kg) and lastly by the Valle Scrivia one (399.5 μg/kg). This latter, however, showed the highest number of VOCs than the other two roses.

The main component of the three rose aromatic water obtained in this study was phenylethyl alcohol (75.3%, 98.3%, and 90.8% for the Damask, Moss, and Valle Scrivia roses respectively), while terpenes showed low concentrations, in agreement with Canbay (2017). Valle Scrivia water was the unique to contain the 2-phenethyl acetate.

According to Hegde and colleagues (2022), the rose species used to produce rose water showed the presence of several major volatile compounds, including linalool, citronellol and geraniol, which is consistent with the findings of this study. Similarly, (Moein et al., 2014) analysed commercial brands of *Rosa damascena* Mill. water, purchased from local markets in Iran and produced with industrial or traditional distillation methods, finding a higher content of phenylethyl alcohol, followed by citronellol, geraniol and trace of benzyl alcohol (Moein et al., 2014), similarly to our findings. Geng and colleagues (2020) also analysed *R. rugosa* water recovered from heat pump process, detecting a higher amount of VOCs found in this study, including citronellol, geraniol and phenylethyl alcohol, but using different temperatures, ranging from 45°C to 55°C, which are higher than those used in this study.

Notably, the phenylethyl alcohol, which is largely present in all three roses, and especially in the Moss one, confers honeyed, spicy, rose and lilac odour; geraniol, which is present in the Damask rose, confers a geranium scent, while 2-phenetyl acetate, which is only present in Valle Scrivia rose, confers a tobacco scent (Flavornet, n.d.).

Thus, condensed water from rose flowers could be used for natural aromatic cosmetic ingredient in lotions, or as a flavoured water in food products.

4. Conclusions

This study provides a comprehensive characterisation of the phytochemical profiles of Damask and Moss roses and, for the first time, the Valle Scrivia moss landrace, highlighting marked genotype-dependent differences in VOCs composition and response to drying. Fresh Damask rose showed the highest total VOC content, dominated by phenyl derivatives (particularly phenylethyl alcohol), together with the highest levels of monoterpenes, benzenoids/phenylpropanoids, and fatty acid derivatives. The Moss and Valle Scrivia roses exhibited lower but comparable VOC levels, with higher relative abundance of sesquiterpenes. Valle Scrivia also displayed a high content of benzenoids/phenylpropanoids, comparable to Damask rose, confirming its distinctive aromatic profile and originality as a local genetic resource.Drying significantly affected both qualitative and quantitative composition, confirming the absence of a universally optimal process.

Heat-pump drying at 30 °C proved more suitable for Damask rose, preserving monoterpenes, and yielding the highest aromatic quality preservation index (AQP). Conversely, HAD at 60 °C was more effective for the Moss rose, while in Valle Scrivia the two methods showed complementary effects.

These findings support the need for genotype-specific optimization of drying conditions.

No harmful Maillard-derived compounds (e.g., furan) were detected, confirming the safety of both drying processes for food and cosmetic applications.

Heat-pump drying additionally enabled recovery of condensed rose waters as a value-added by-product. Although less concentrated than petals, these retained relevant VOCs, particularly phenylethyl alcohol, supporting their potential uses as natural ingredients in cosmetic and food formulations, within a circular economy framework.Overall this study confirms the industrial relevance of traditional rose varieties, and provides the first evidence of the phytochemical potential of the Valle Scrivia landrace, supporting its valorisation. Future work should address sensory-chemical correlations, optimization of drying parameters, and shelf-life stability.

CRediT authorship contribution statement

Giuseppe Zeppa: Writing – review & editing, Supervision, Conceptualization. **Simone Ravetto Enri:** Data curation. **Manuela Giordano:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Nicole Mélanie Falla:** Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Valentina Scariot:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

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Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.indcrop.2026.123652.

Data Availability

Data will be made available on request.

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