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Abstract

Comprehensive two-dimensional gas chromatography (GC×GC) is the most effective multidimensional separation technique for in-depth investigations of complex samples of volatiles (VOC) in food. However, each analytical run produces dense, multi-dimensional data, so elaboration and interpretation of chemical information is challenging.

This study exploits recent advances of GC×GC-MS chromatographic fingerprinting to study VOCs distributions from Extra Virgin Olive Oil (EVOO) samples of a single botanical origin (Picual), cultivated in well-defined plots in Granada (Spain), and harvested at different maturation stages. A new integrated work-flow, fully supported by dedicated and automated software tools, combines *untargeted* and *targeted* (*UT*) approaches based on peak-region features to achieve the most inclusive fingerprinting.

Combined results from untargeted and targeted methods are consistent, reliable, and informative on discriminant features (analytes) correlated with optimal ripening of olive fruits and sensory quality of EVOOs. The great flexibility of the *UT fingerprinting* here adopted enables retrospective analysis with great confidence and provides data to validate the transferability of ripening indicators ((*Z*)-3-hexenal, (*Z*)-2-hexenal, (*E*)-2-pentenal, nonanal, 6-methyl-5-hepten-2-one, octane) to external samples sets. Direct image comparison, based on *visual* features, also is investigated for quick and effective pair-wise investigations. Its implementation with reliable metadata generated by *UT fingerprinting* confirms the maturity of 2D data elaboration tools and makes advanced image processing a real perspective.

Key-words:

Comprehensive two-dimensional gas chromatography-mass spectrometry; untargeted and targeted fingerprinting ; extra virgin olive oil; olives ripening; retrospective investigations

1. Introduction

Comprehensive two-dimensional gas chromatography (GC×GC) is the most effective multidimensional separation technique for in-depth investigations of complex samples of volatiles in food [1]. The combination, in a single analytical platform, of two separation dimensions with mass spectrometric detection and, when possible, automated sample preparation, delivers highly efficient sample profiling (detailed analysis of single molecular entities) and fingerprinting (rapid, high-throughput screening of samples for distinctive analytical signatures) [2].

Each analytical run produces dense, multi-dimensional data, so elaboration and interpretation of chemical information is a challenging task. In addition, food samples generally have a high-degree of chemical multidimensionality [3] thus creating highly complex analytical challenges. In this context, data elaboration strategies should implement smart and productive processes, preferably with a high degree of automation, to make cross-samples analysis efficient and informative.

Within the existing methodologies for GC×GC data elaboration [4,5], the approach based on *peak-region* features has been very effective because of its comprehensive and uniform treatment of information from each sample constituent, both knowns and unknowns. Each single chemical entity is characterized by its chromatographic and spectrometric parameters (retention time in both dimensions, detector response, and mass spectral information) and by its absolute and relative position within the pattern of all detectable constituents. As a consequence, the 2D peak-retention pattern of a sample is a diagnostic fingerprint, informative of its composition; and pattern recognition approaches can be successfully applied to improve effectiveness and productivity in multi-sample data elaboration.

Although these concepts are not new for the GC×GC community [6], the full automation of these procedures and their implementation in commercial software packages has been achieved only recently. This has limited both routine adoption of the technique for food analysis and investigative strategies for profiling [2,7].

Analysis of olive oil volatiles is a challenging and important problem and GC×GC can yield deeper knowledge of the composition of this fraction offering new perspectives for quality and authenticity assessment [8].

In spite of the great potential of GC×GC, few studies are available in this field. Vaz Freire et al. [9]first proposed an image-features approach, or more generally a pattern recognition methodology, to investigate the characteristic distribution of volatiles from oils. They adopted open-source image analysis software (Image J, National Institutes of Health) to extract information from small 2D regions located over the separation space and, by Principal

Component Analysis (PCA), selected those regions with the highest discrimination potential. Then, they used targeted profiling to locate known analytes within informative 2D regions.

In 2010, Cajka and co-workers [10] exploited the targeted profiling potential of GC×GC-ToF-MS and identified 44 analytes able to discriminate samples of different geographical origin and production year. More recently, Purcaro et al. [8] combined targeted and untargeted analysis with the goal of a chemical blueprint of olive oil aroma defects. This inter-laboratory study confirmed the reliability of GC×GC for detailed profiling of olive oil volatile fractions and introduced an iterative strategy [11,12] to locate sensory-relevant analytes efficiently.

This study exploits the most recent advances of GC×GC-MS chromatographic fingerprinting to study VOC distributions from Extra Virgin Olive Oil (EVOO) samples of a single botanical origin (Picual), cultivated in well-defined plots in a single region (Granada, Spain), and harvested at different maturation stages. The principal interest in this application is the quality characteristics related to optimal ripening of olive fruits [**13**,**14**]**15**,**16**,**17**,**18**,**19**,**20**,**21**] and, as a consequence, olive oil classification and perceivable sensory quality [**22**,**23**]. In particular, this study proposes an integrated work-flow, fully supported by dedicated software tools, that performs cross-samples comparisons by contemporarily considering characteristic distributions (i.e., sample fingerprints) of both known and unknown compounds. This work-flow integrates both *untargeted* and *targeted* (*UT*) *fingerprinting* to realize the most comprehensive results, and so is termed *UT fingerprinting*. Challenges of retrospective analysis and immediacy of image fingerprinting also are discussed because of the advantages they offer in specific investigations.

2. Materials and methods

2.1. Reference compounds and solvents

Pure reference standards of α-thujone, used as Internal Standard (ISTD), at a concentration of 100 mg/L in dibuthyl phthalate, and *n*-alkanes (n-C9 to n-C25), used for linear retention index (I^T_S) determination, at a concentration of 100 mg/L in cyclohexane, were supplied by Sigma-Aldrich (Milan, Italy).

Solvents for *n*-alkanes dilution (toluene and cyclohexane HPLC-grade) and dibuthyl phthalate also were from Sigma-Aldrich.

2.2. Olive oil samples

Olive oil samples of *Picual* variety, harvested in 2014, were supplied by "GDR Altiplano de Granada" (Spain) and were obtained from olives harvested in three different plots in Granada: "812 *Caniles*" (organic production and drip irrigation); "233-234 *Baza*" (conventional production and drip irrigation); and "701 *Benamaurel*" (conventional production and drip irrigation).

Each sample was available in duplicate and obtained by mixing olives from at least five different trees in the same plot to have homogeneous and representative samples. Olives were harvested at four different ripening stages: November 10-12, 2014; November 24-28, 2014; December 16-17, 2014; and January 12-15, 2015.

Samples were analyzed by an accredited laboratory to define quality parameters: acidity (%), peroxide index (mEq O_2/kg), and UV absorption. Samples also were submitted to sensory evaluation by a recognized/official panel [24]. Sample descriptions and acronyms are reported in **Table 1**, together with quality assessments**.**

2.3. Head-space Solid Phase Micro Extraction sampling devices and conditions

Volatiles were sampled from the headspace (HS) by HS Solid Phase Micro Extraction (HS-SPME). The sampling protocol was optimized in a previous study [8] and employs a divinylbenzene/carboxen/polydimethylsiloxane (DVB/CAR/PDMS) 50/30 µm, 2 cm length stableflex fiber from Supelco (Bellefonte, PA, USA).

The ISTD (α-tujone) was pre-loaded onto the fiber before sampling through the standard-in-fiber procedure. An ISTD solution, 2.0 µL, was placed into a 20 mL glass vial and submitted to HS-SPME at 50°C for 15 minutes (min). The fiber then was exposed to the head-space of olive oil samples (1.500 g exactly weighted) in 20 mL glass vials, at 50°C for 40 minutes. Last, the sampled analytes were recovered by introducing the fiber into the S/SL injection port of the

GC×GC system at 260°C and thermally desorbed for 5 minutes. Each sample was analyzed in duplicate.

2.4. Comprehensive two-dimensional gas chromatographic system (GC×GC-MS) set-up and analysis conditions

GC×GC analyses were performed on an Agilent 6890 unit coupled to an Agilent 5975C MS detector (Agilent, Little Falls, DE, USA) operating in EI mode at 70eV. The GC transfer line was set at 270°C and the MS scan range was 40-240 *m/z* with a scanning rate of 12,500 amu/s to obtain a spectra generation frequency of 30 Hz.

The system was equipped with a two-stage KT 2004 loop-type thermal modulator (Zoex Corporation, Houston, TX) cooled with liquid nitrogen and with the hot jet pulse time set at 250 ms with a modulation time of 4 s for all experiments. Fused silica capillary loop dimensions were 1.0 m long and 0.1 mm inner diameter. The column set was configured as follows: ^{1}D SolGel-Wax column (100% polyethylene glycol)(30 m × 0.25 mm d_c, 0.25 µm d_f) from SGE Analytical Science (Ringwood, Austalia) coupled with a ^{2}D OV1701 column (86% polydimethylsiloxane, 7% phenyl, 7% cyanopropyl) (1 m × 0.1 mm d_c, 0.10 µm d_f) from Mega (Legnano, Milan, Italy).

Fiber thermal desorption into the GC injector port was under the following conditions: split/splitless injector in split mode, split ratio 1:20, injector temperature 250°C. Carrier gas was helium at a constant flow of 1.8 mL/min. The temperature program was: from 40°C (1 min) to 200°C at 3°C/min and to 250°C at 10°C/min (5 min).

The *n*-alkanes liquid sample solution for I^T_S determination was analyzed under the following conditions: split/splitless injector in split mode, split ratio 1:50, injector temperature 280°C, injection volume 1µL.

2.5. Raw data acquisition and GC×GC data handling

Data were acquired by Agilent MSD ChemStation ver E.02.01.00 and processed using GC Image GC×GC Software version 2.5 (GC Image, LLC Lincoln NE, USA). Statistical analysis was performed by XLstat (Addinsoft, New York, NY USA) and the PLS Toolbox (Eigenvector Research Inc., West Eaglerock Drive, Wenatchee, WA, USA) for Matlab® software (The Mathworks Inc., Natick, MA, USA).

2.6 Profiling and advanced fingerprinting work-flow

The bi-dimensional chromatographic data elaboration proposed here was organized in a sequential work-flow illustrated in **Figure 1**.

Insert here Figure 1

Untargeted and targeted analyses were performed by applying the *template matching* fingerprinting strategy, introduced by Reichenbach et al. in 2009 [6]. It uses the patterns of 2D peaks' metadata (retention times, MS fragmentation patterns, and detector responses) to establish reliable correspondences between the same chemical entities across multiple chromatograms. The output of template matching fingerprinting is a data matrix of aligned 2D peaks and/or peak-regions, together with their related metadata (^{1}D and ^{2}D retention times, compound names for target analytes, fragmentation pattern, single ions or total ions response), that can be used for comparative purposes.

Targeted analysis (Step 1 of **Figure 1**) focused on about 120 selected compounds, each reliably identified by matching their EI-MS fragmentation pattern (NIST MS Search algorithm, ver 2.0, National Institute of Standards and Technology, Gaithersburg, MD, USA, with Direct Matching threshold 900 and Reverse Matching threshold 950) with those collected in commercial (NIST2014 and Wiley 7n) and in-house databases. As a further parameter to support reliable identification, Linear Retention Indices (I^T_S) were considered and experimental values compared with tabulated ones.

Untargeted analysis (Step 2 of **Figure 1**) was based on a *peak-regions* features approach [5] and was performed automatically by GC Image Investigator™ R2.5 (GC-Image LLC, Lincoln NE, USA). The untargeted analysis included all *peak-regions* above the arbitrarily fixed peak response threshold of 5,000 counts together with target peaks from Step 1. This approach [25,26,27,28], briefly described in *Section 3.2*, re-aligned the 48 chromatograms using a set of *registration peaks*. The resulting data matrix was a 48 × 600 (samples × reliable *peak-regions*). Response data from aligned 2D *peak-regions* were used for PCA and results cross-compared to those obtained from target peaks distributions. (See *Section 3.2* for the discussion of results.)

Visual features fingerprinting, performed as pair-wise image comparison, was the last step of the study (Step 4 of **Figure 1**) and was rendered with "colorized fuzzy ratio" mode [cite Hollingsworth et al., JoCA 1105:51, 2006]. The algorithm computes the difference at each data point between pairs of TICs; a data point is the output of the detector at a point in time. These differences are mapped into Hue-Intensity-Saturation (HIS) color space to create an image for visualizing the relative differences between image pairs in the retention-times plane [29].. A detailed description is provided in *Section 3.4*.

3. Results and discussion

The goal of this study was to evaluate the potential of combining *U*ntargeted and *T*argeted 2D data elaboration approaches based on untargeted *peak-region* features, target peaks, and *visual* features to approach to the most inclusive fingerprinting within EVOO volatiles: the *UT fingerprinting* strategy. Based on a sampling design focused on a single botanical variety and well-defined geographical locations, VOCs fingerprints were interpreted as a function of ripening stage and oil quality.

This strategy was inspired by a previous study focused on olive oil aroma defects [8], in which results clearly indicated that the informative potential of GC×GC-MS to delineate specific fingerprints for sensory quality classification of oils. These results showed that a "*strictly structured experimental design (considering more variables, such as cultivar, geographical origin, etc.)*" would be mandatory to "*robustly and reliably characterize specific markers and related characteristics concentration windows*" to support, or even replace, sensory evaluation [8]. In addition, it was clear that larger numbers of "external variables" affecting VOCs pattern reduce the effectiveness of untargeted approaches.

In the present study, with fewer sample-set variables, and a data elaboration process that combines untargeted and targeted approaches (i.e., *peak-region features, peaks,* and *visual features* methods), we achieve highly effective fingerprinting. The proposed work-flow is comprehensive yet efficient and fully supported by new commercial software. In addition, we validate both the data elaboration strategy and the informative role of some targets by a retrospective investigation on VOCs patterns from EVOO, VOO, and *lampante* oils (LOO) analyzed in previous studies.

Following this scheme, we first present and discuss results from targeted analysis, focusing on peaks for known informative chemicals and selected VOCs strictly related to the olives' geographical location, ripening stage, and product (oils) quality (presence/absence of sensory defects). Next, untargeted analysis based on peak-regions features, implemented in the second step, is discussed from the perspective of: (a) confirming sample classification results; (b) indicating new potential targets; (c) defining chemical indexes of ripening and quality through the ratio between informative analytes; and (d) validating the role of informative ratios through retrospective elaboration of samples analyzed in previous studies by adopting the *UT* template created on the current sample set. The last part of the study aims at determining if classification based on peak-regions features could be replaced by direct image comparison without losing information about the chemical composition of this fraction. The following paragraphs illustrate the research steps and critically discuss results.

3.1 Targeted analysis and samples discrimination

The sample set is reported in **Table 1** with their quality parameters, sensory evaluation results, and commercial classification. Quality metrics (acidity %, peroxide index, UV absorbance, and organoleptic assessment) indicated that 6 of the 24 samples were not compliant with *Extra-Virgin* classification [30]. These samples, classified as *Virgin* (VOO) and *Lampante* (LOO), were from the late ripening stages of the *Baza* and *Benamaurel* plots. This quality classification was confirmed by replicate sampling (i.e., *Baz_3_1/_2 and Baz_4_1/_2; Ben_4_1/_2*) and was related to sensory defects revealed by the panel (Median of defects - Md >0.00). In addition, low-quality samples were connoted by a higher peroxide index and acidity %.

From the available literature [**31**,**32**,**33**,**34**,**35**,**36**,**37**,**38**,**39**], analytes detected in the GC×GC data were identified by their EI-MS fragmentation pattern and Linear Retention Indices (I^{T}_{S}) (see *section 2.6* for details). Following the work-flow in **Figure 1**, *template-matching* fingerprinting (see Paragraph *2.6*) with 119 target peaks was used to map these informative chemicals across samples.

Figures 2A-B shows the pseudocolorized GC×GC chromatogram of an EVOO sample from the *Benamaurel* plot harvested at stage 4 (in January 2015). **Figure 2B** locates the 119 known target peaks (empty light green circles) linked to the ISTD (α-tujone black circle) by red lines.

Place here Figures 2A-E

The quali-quantitative distribution of VOCs changed with the harvest stages. The number of detectable peaks above a Volume threshold of 4,000 (arbitrarily fixed on the Total Ion Current signal) was about 270-280 at the first stage and reached about 360 at the final stage (data not shown).

The effectiveness of GC×GC, in both peak-capacity and overall chromatographic resolution, plays a critical role in isolating the information for compounds with similar retention times in the ^{1}D dimension. A zoomed region, highlighted in **Fig 2C,** emphasizes the retention area of highly volatile compounds in which some branched hydrocarbons (eluting later in the ^{2}D) are separated along the ^{2}D from saturated and unsaturated and carbonyl compounds (e.g., pentanal, hexanal, (*E*)-2-butenal), and 1-penten-3-one, an odor-active volatile deriving from linolenic acid degradation), and alcohols (e.g., 1-propanol, 2-butanol, and 2-methyl-2-propanol).

The relative distribution (Normalized 2D Peak Volumes) of the 119 peaks is illustrated as heat-map in **Supplementary Figure 1** (**SF1**). Columns are ordered left-to-right by ^{1}D retention indices

(polar phase column, 100% polyethylene glycol). The logarithmic colour map is based on 2D-Peak Volumes divided by ISTD response and is normalized by dividing single values by row standard deviations.

Table 2 reports the 119 target compounds together with their ^{1}D and ^{2}D retention times, I^{T}_{S}, sensory descriptors, and correlation with oil defects as reported in reference literature [31,32,33,34,35,36,37,38,39]. 2D Peak Normalized Volumes (average values of two analytical replicates) are provided as Supplementary information (**Supplementary Table 1- ST1**).

The target analytes distribution (Normalized 2D volumes) was adopted as an informative fingerprint for possible discrimination of samples within different harvest stages and, in particular, to locate and validate specific indicators of ripeness, and, when feasible, odor-active compounds related to sensory quality.

Principal Component Analysis (PCA) maps the natural, unsupervised conformation of samples' groups and sub-groups [40]. **Figure 3A** shows the scores plot on the first two principal components (F1-F2 plane), based on the 48 × 119 matrix (samples × targets). The variance from the first principal component (F1) was 30.64% while for the second principal component (F2) was 10.06%. Autoscaling and mean centering were applied as pre-processing methods, because baseline correction already was applied for 2D data elaboration by GC Image. The corresponding loading plots are available as Supplementary information (**Supplementary Figure SF2A**).

Insert here Figures 3A-B

The PCA shows a clear discrimination between EVOO and VOO (clustered together in the right side) and *LOO* samples. Additionally, a further sub-classification according to harvesting stage is evident along F2 and within EVOO samples (see arrow).

The samples' structure/classification over the PCA loading plot (see Supplementary Information **SF2A**) indicates those analytes that are effectively responsible for the discrimination of *lampante* oils (stage 4 of *Benamaurel* and *Baza*). These analytes include saturated (e.g., heptanal, octanal, and nonanal) and unsaturated (e.g., (*E*)-2-heptenal) aldehydes, well-known from the literature to be correlated with specific sensory defects of olive oils. Moreover, the separation of *lampante* oils is also driven by other compounds, including some alcohols (e.g., propan-1-ol, 1-octen-3-ol, heptan-1-ol, and octan-1-ol), ketones (e.g., heptan-2-one and octan-2-one) and esters (e.g., ethyl acetate, ethyl-2-methyl butanoate, and ethyl-3-methyl butanoate).

Additional insight on the targets' distribution as a function of harvest time was obtained by independently processing single subsets of samples by geographical location. In this way, all variables related to the pedoclimatic conditions and field treatments (organic or conventional) were excluded, and indications on variables (markers) correlated with ripening stage are more clearly evidenced. **Figure 3B** shows the score plot for the *Caniles* EVOO subset and the corresponding loadings plot is provided as Supplementary information (**Supplementary Figure 2B -SF2B**).

Compounds that contribute most to discriminating harvest stage 1 are: (*Z*)-2-hexenal, connoted by a *fruity* note; (*Z*)-3-hexenal, with *green* odor; and (*E*,*E*)-2,4-hexadienal, contributing a *fresh* note to the overall perception. A group of unsaturated hydrocarbons, tentatively identified from the literature [41], was found to be distinctive in the discrimination of the earlier harvest stages (1-2): 3,4-diethyl-1,5-hexadiene (RS+SR), 3,4-diethyl-1,5-hexadiene (meso), (5*Z*)-3-Ethyl-1,5-octadiene, (5*E*)-3-Ethyl-1,5-octadiene, (*E*,*Z*)-3,7-decadiene, (*E*,*E*)-3,7-decadiene, and (*E*)-4,8-Dimethyl-1,3,7-nonatriene. As expected, all these markers decrease in later ripening stages.

Interestingly, but not surprisingly, the evolution of (*Z*)-2-hexenal and (*Z*)-3-hexenal, which provide a fruity note (Mf), through time is in accordance with the sensory evaluation of the panel (as reported in **Table 1**). The relative abundance of these analytes shows a marked decrease from samples harvested in November (2014) to late January (2015). This observation is confirmed by data from *Baza* oils where (*Z*)-3-hexenal falls below method Limit of Detection (LOD) at stages 3 and 4 consistent with the perception of defects (Md>0.00) leading to their classification as *lampante* oils, while (*Z*)-2-hexenal in *Benamaurel* samples was not detected even at first harvesting time.

On the other hand, some other target analytes, for example octane (*sweety*, *alcane*), nonanal (*fatty*, *waxy*), and 6-methyl-5-hepten-2-one (*pungent*, *green*), showed an opposite trend by increasing their relative abundance from stage 1 to the 4. Their presence was not revealed by the panel, possibly because of their relatively high odor thresholds (octane 940 µg/Kg, nonanal 150 µg/Kg, and 6-methyl-5-hepten-2-one 1000 µg/Kg [22]).

These results are consistent with those reported by Aparicio and Morales [**19**], Raffo et al. [**42**] and other researchers [**22**,**43**] who hypothesized an increase of autoxidation products (e.g., octane and 6-methyl-5-hepten-2-one) accompanied by a decrease of lipoxygenase pathway products (e.g., (*Z*)-2-hexenal, (*Z*)-3-hexenal, and (*E*,*E*)-2,4-hexadienal) with later harvest times.

PCA carried out on *Baza* and *Benamaurel* oils (scores and loadings provided as Supplementary information, **Supplementary Figures 3A** and **3B - SF3A** and **SF3B**) confirms, with some

exceptions (e.g., in *Benamaurel* samples), the distribution of the samples and the trend of these specific chemicals over time from stage 1 to 4.

3.2. Untargeted analysis

Untargeted analysis was performed to extend the comparative process to the entire pattern of detected VOCs. The unsupervised fingerprinting was based on the peak-region feature approach and implemented by Image Investigator in the GC Image software package. This data elaboration step was made more informative by considering the 2D peaks included in the targeted template built within the Step 1 of the work-flow (illustrated in **Figure 1**), thus preserving all information about known analytes within the fingerprinting.

The fully automated procedure of *peak-regions* fingerprinting delineates a small 2D retention-times window (or *region*) per 2D *peak* over the chromatographic space. Regions are shown in **Figures 2B** and **2D,** delineated with light blue graphics. In this context, the process approaches "one-feature-to-one-analyte" selectivity, typical of peak features methods, with all the advantages of regional features matching [5,27,28]. These advantages includes unambiguous cross-detection/matching of trace peaks that may be detected in some samples but not in others and co-eluting analytes that may be resolved in some chromatograms but not in others.

The unsupervised procedure is:

1. Detect and record 2D peaks in individual chromatograms.
2. Locate *registration* peaks, i.e., peaks that reliably match across all chromatograms (connoted by red circles in **Figures 2D** and **2E**). This is verified for a sub-group of targeted peaks.
3. Align and combine all chromatograms to create a composite chromatogram [5].
4. Define a pattern of *region* features around every 2D peak detected in the composite chromatogram.
5. Create a combined targeted and untargeted template from:
    a. the registration peaks from Step 2,
    b. the peak-regions from Step 4, and
    c. the targeted peaks.

The programmed output of the Image Investigator is the template that includes only (a) and (b). An innovation of this work is the addition of (c) targeted peaks.

Once the resulting template, as shown in **Figure 2B** superimposed on the image of the *Baz_4_1* sample - analytical replicate 1, is matched to a target chromatogram, the analysis includes peak-regions (light blue graphics), targeted peaks (green circles), and registration peaks (red circles). Feature regions are aligned relative to corresponding peaks, and the characteristics of

those features including all metadata (retention times in both chromatographic dimensions, detector response, relative/absolute intensity, peaks' EI-MS fragmentation pattern, response factors, etc.) are computed to create a feature vector for the target chromatogram to be adopted for cross-sample analysis. The final output is a data matrix where peak-regions and template peaks are cross-aligned within all samples' chromatograms and the response data are available for further chemometrics.

Results based on 180 reliable peak-regions (i.e., those that matched in all-but-one chromatogram of the set) are shown in **Figure 2B**, and visualized by PCA of **Figure 4A.** They confirmed what already was evidenced by the known targets distribution: a clear discrimination of *lampante* oils from VOO and EVOO while maintaining the sub-classification based on harvesting period. These results account for a total variability of 42%, in line with previous elaborations.

Targeted peak-regions cross-validate the classification based on PCA: (*Z*)-2-hexenal, (*Z*)-3-hexenal, (*E*,*E*)-2,4-hexadienal, 1,4-pentadiene, (5*Z*)-3-ethyl-1,5-octadiene, and (*E*)-4,8-dimethyl-1,3,7-nonatriene contribute to the discrimination of stages 1 and 2 against the others, as obtained in the previous elaboration. Untargeted analysis does not discover additional informative roles of un-identified features and confirms the coverage of the targeted peaks.

One interesting and positive aspect of these results is the strong accordance between targeted and untargeted fingerprinting in terms of sample discrimination effectiveness. This result was not observed when, for example, sampling conditions included too many variables known to impact the VOCs fingerprint (e.g., cultivars, geographical origin, harvesting period/year, technological process, bad practices etc.) [8]. In those less-controlled cases, the sensitivity and effectiveness of untargeted methodologies were lower and targeted analysis gave better results. In such cases with more experimental variables, much larger numbers of samples may be required for effective discrimination.

Another interesting outcome, in line with previous studies on flavor blueprint [8], is the accordance between sensory quality scores and samples sub-classes. Because sensory profiles by descriptive analysis were not available, a direct correlation between odor-active compounds distribution and sensory quality was not possible. However, positive attributes (Mf in **Table 1**) had high scores for samples harvested at stages 1 and 2 that rapidly decreased at stages 3 to 4. Along the same Principal Component (e.g., F2) samples discrimination is in accordance with both variables (i.e., quality score and ripening stage).

Cross-validation of fingerprinting results reinforces and confirms the role played by some ripening markers responsible for positive attributes (green, fruity and fresh) [22,34]. These

compounds appear at stage 1, last up to the stage 2, and then start to decrease. From these results, and in agreement with quality parameters (**Table 1**), the optimal harvest period to obtain a product with high sensory quality from *Picual* variety appears to have been November within stages 1 and 2.

Several informative analytes positively and/or negatively correlated with ripening and oil quality, were therefore selected and their ratio profiled as a function of harvest stages. In addition, a retrospective analysis on EVOO samples' pattern acquired during a previous study [8] was performed to verify the reliability and consistency of these indicators.

3.3 Retrospective analysis and definition of reliable chemical indexes of ripening

Relative ratios (based on 2D Peak Volumes) from the informative chemicals highlighted by the *UT fingerprinting* were calculated and trends observed along harvest stages.

These ratios are functions of sampling parameters (phase ratio, β; sampling temperature; and time), but derive from analyses conducted under highly standardized and head-space linearity conditions. These VOCs fingerprints are therefore informative and replicable, and these ratios could be transferred to other studies/ batches and considered as chemical indices of ripening.

Analytes chosen to discriminate samples at stages 1 and 2 were: (*Z*)-2-Hexenal, (*Z*)-3-Hexenal, (*E*)-2-Pentenal, and (*E,E*)-2,4-Hexadienal; those chosen that contributed to discriminate the late harvest stage were: octane, 6-methyl-5-hepten-2-one, and nonanal. Their ratios for the *Baza* samples set are illustrated by the box-plot graphics in **Figure 5** and correspond to: (*Z*)-3-Hexenal/6-Methyl-5-hepten-2-one, (*Z*)-3-Hexenal/Nonanal, (*Z*)-2-Hexenal/6-Methyl-5-hepten-2-one, (*E,E*)-2,4-Hexadienal/6-Methyl-5-hepten-2-one, (*Z*)-3-Hexenal/Octane, (*E*)-2-Pentenal/Nonanal, (*E*)-2-Pentenal/6-Methyl-5-hepten-2-one, and (*E*)-2-Pentenal/Octane. Trends were estimated by fittings with exponential, polynomial, or linear functions to delineate their evolution along harvest stage, resulting functions are reported in **Table 3**. The accuracy of fittings is as assessed by the determination coefficient (R^2).

Insert here Figure 5

As a general consideration, most of the ratios followed an exponential or second order polynomial trend with the exception of (*E*)-2-pentenal/octane index whose evolution was relatively linear. In addition, non-linear trends are connoted by higher informative potential because of their sudden changes between optimal and non-optimal ripening stages. Notably, their numeric values decreased one order-of-magnitude between harvest stages where oil quality changed from EVO to VO or *lampante*.

The usefulness of such ratios also might be evaluated from a wider perspective where, for example, VOCs fingerprints are adopted for quality classification of EVO oils. Within selected volatiles produced during the climacteric stage of ripening [**22**], (*Z*)-3-hexenal is a product of the lipoxygenase pathway and, in EVO and VO oils, it contributes to the fresh aroma perception thanks to its relatively low odor threshold [**20**,**21**,**34**,**37**]. This compound is also a cultivar-specific marker for the *Picual* variety [**34**], as is 6-methyl-5-hepten-2-one that, as a counterpart, is connoted by a negative odor perception and an incremental trend along ripening stages. Nonanal provides information about oxidation state as well as octane [**36**,**37,44**,**45**].

To evaluate the consistency and the transferability of this approach for informative chemical indexes, a retrospective analysis was attempted by re-processing chromatograms from a previous study [8]. Samples consisted of EVOO from different botanical/geographical origins and technological processes and from olives harvested in 2013. They were analyzed previously, in the authors' laboratory, with the same nominal HS-SPME sampling protocol and GC×GC-MS conditions. Details are reported in **Table 1**.

The peak-regions template created in this study (and shown in **Figure 6A** with the *Can_1_2* sample) was matched to these older, GCxGC chromatograms (as shown in **Figure 6B** with the EVOO oil from Sicily PDO Monti Iblei) after a supervised transformation of the template to compensate for non-linear retention times differences in both dimensions [46].

Insert here Figures 6A-B

These chromatographic inconsistencies are not infrequent because, in a time frame of two years, column sets were replaced and/or columns have altered retention behaviour (in particular the 1D PEG polar phase) producing minimal, but not negligible, pattern alterations. However, thanks to the specificity of the matching methods, 2D peaks that positively match are just those with EI-MS fragmentation pattern similarity above 700 (direct match) or 900 (reverse match). Cross-aligned results are in consequence reliable and consistent, making possible retrospective investigations.

Ratios between informative markers for the EVOO samples from *Baza*, *Caniles,* and *Benamaurel*, plus five samples from the previous study (R-EVOO from 1 to 5), were analyzed by PCA and the results are shown in **Figure 4B**. The discrimination power of the first two PCs reaches 94%, confirming the informative power of the combination of variables. Picual samples (*Baz*, *Can* and *Ben*) are clustered together, with the exception of the *Benamaurel* EVOO at the earliest harvest stage, whereas along F2, there is evident discrimination for

ripening stage. On the other hand, R-EVOO samples clustered together close to stages 2 and 3, with the only exception of R-EVOO 2 PDO (Monti Iblei Sicily, Italy), which showed a very high value for (Z)-3-Hexenal/6-Methyl-5-hepten-2-one because of the high abundance of (Z)-3-Hexenal (which accounted for 12% of Total Volume). The corresponding loading plot for informative rations is provides as Supplentary information **Supplementary Figure 4B** - **SF4B**.

The proposed ratios are consistent within Picual variety, but to be considered as general indices for ripening classification their reliability should be verified and validated by analyzing samples from different harvest years and location, and their transferability to other botanical origins and geographical locations should be investigated ex-novo by screening samples after a rigorous sampling design.

3.4 Fingerprinting by image features approach

The last part of this study focuses on a fingerprinting approach based on *visual* features and it is suitable for rapid and effective pair-wise pattern comparisons. The approach is one of the earliest introduced in GC×GC data elaboration [5], and is still adopted when distinctive patterns have to be compared on an untargeted basis to immediately reveal compositional differences.

Previous studies demonstrated the potentials of this simple and intuitive approach by exploring the volatile fraction of roasted coffee and juniper [47], volatiles emitted from *Chrysolina herbacea* bugs fed by *Mentha* spp. leaves [48], and primary metabolites distribution in mice urine after dietary manipulation [26]. The same approach was used iteratively, by cross matching sample pairs, to reveal a chemical blueprint of odor active compounds responsible of sensory defects [8].

In this application, where VOCs variations are mainly related to harvest/ripening stage, the visual approach would be effective to immediately highlight 2D peaks and/or analytes that have significantly different relative distributions between sample pairs. In addition, by comparing samples within the same production plot, the effect of fruit maturation is magnified while keeping constant the effect of local pedoclimatic changes.

This fully automated approach, namely Image Comparison (GC Image v2.5b), if implemented with peak-regions fingerprinting template, provides immediate information about targeted or untargeted peak-regions variations between pair-wise compared samples.

The example here illustrated refers to a *Benamaurel* oil sample obtained at stage 1 (averaged normalized image from *Ben_1_1 and Ben_1_2*) arbitrarily considered as the *analyzed* image *versus* the stage 4 samples (averaged normalized image from *Ben_4_1 and Ben_4_2*) arbitrarily considered as the *reference* image.

Figure 7 shows the image comparison results between the average image of harvest stage 1 (**Fig. 7A**) and stage 4 (**Fig. 7B**) obtained by averaging the 2D chromatograms from two replicate locations and two analytical runs. The resulting image (**Fig. 7C**) is rendered as "colorized fuzzy ratio" that uses the Hue-Intensity-Saturation (HIS) color space to color each pixel in the retention-times plane. The algorithm computes the difference at each data point between aligned pair-wise images. If a pixel is colored green, then the difference is positive, indicating a larger detector response in the *analyzed* image (*Ben_1_1 and Ben_1_2*). If a pixel is colored red, then the difference is negative, indicating a larger detector response in the *reference* image (*Ben_4_1 and Ben_4_2*). Brightness depends on the magnitude of the difference, and so white saturation indicates pixels at which peaks have detector responses that are nearly equal in the analyzed and reference images.

Insert here Figures 7A-C

Because the 2D chromatograms submitted to the image comparison were already pre-processed by *peak-region* fingerprinting, results are implemented with the information about 2D peaks' identity (if known) or unique identification numbering (#) for unknowns.

Results of *visual* features fingerprinting are intuitive and promptly give information on discriminant peaks. Green colored regions in the upper part of the 2D plot at lower ^{1}D retention correspond to unsaturated alkanes [41] (#ID 10, 11, 15, 17, 21), unsaturated aldehyes (#30 (E)-2-Pentenal, #32 (Z)-3-Hexenal, #34 (E)-3-Hexenal, #42 (Z)-2-Hexenal, #44 (E)-2-Hexenal, #71 (E,Z)-2,4-Hexadienal, and #73 (E,E)-2,4-Hexadienal), whereas red areas corresponds to limonene (#41), short chain fatty acids (#107 hexanoic, #115 octanoic and #117 nonanoic acid), linear saturated aldehydes (#12 pentanal, #54 octanal and #70 decanal), and some ketones, such as 6-methyl-5-hepten-2-one (#63).

4. Conclusions

This study evidences and emphasizes the potentials of fingerprinting based on GC×GC-MS separations and highlights the synergism between untargeted and targeted methodologies to investigate complex fractions of volatiles in depth. Their combination enables to achieve the most inclusive/comprehensive fingerprinting (*UT fingerprinting*) and if compared to previous studies, the degree of automation implemented in the data elaboration work-flow is promising. Experimental results on EVOO volatiles definitely confirm the maturity of available software tools to exploit dense and multi-level data set effectively.

The consistency and reliability of cross-sample analysis results in revealing informative/discriminant features is confirmed by matching results from different approaches, and is of interest in this challenging application field where accurate fingerprinting can be very useful: (a) to support studies aimed at improving product quality; (b) to define a distinctive chemical fingerprint to discriminate samples of a certain botanical/geographical origin; and (c) to re-investigate, on a retrospective projection, samples in light of new informative features.

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Note: S. E. Reichenbach has a financial interest in GC Image, LLC.

Figure Captions:

Figure 1: Two-dimensional chromatographic data elaboration work-flow.

Figures 2A-E: (**2A**) Pseudocolorized GC×GC chromatogram of *Ben_4_1* harvested at stage 4 (in January 2015). (**2B**) Position of the 119 known target peaks (empty light green circles) linked to the ISTD (α-tujone black circle) by red lines. (**2C**) Retention area of highly volatile compounds referred to the white rectangle of Fig. 2A. (**2D**) Peak-regions delineated by light blue graphics together with targeted peaks (empty light blue circles). (2E) Results of comprehensive template matching for peak-regions, target peaks (green circles) and registration peaks (red circles). For details see text.

Figures 3A-B: PCA results. (**3A**) Scores plot on the first two principal components (F1-F2 plane), based on targets distribution across all samples (48 × 119 matrix - samples × targets). (**3B**) Scores plot the first two principal components (F1-F2 plane) based on targets distribution across *Caniles* EVOO subset.

Figures 4A-B: PCA results. (**4A**) Scores plot on the first two principal components (F1-F2 plane), based on reliable *peak-regions* distribution across all samples (48 × 180 matrix - samples × reliable *peak-regions*). (**3B**) Scores plot the first two principal components (F1-F2 plane) based on informative ratios between ripening markers. For details see text.

Figure 5: Box-plot graphics showing the evolution of different informative ratios between ripening markers along harvest stages for Baza plot samples.

Figures 6A-B: (**6A**) 2D chromatogram of *Can_1_2* sample together with the reliable peak-regions template. (**6B**) 2D chromatogram of *R-EVOO 2* sample (PDO Monti Iblei - Sicily Italy) together with the reliable peak-regions template tranformed and adapted with a supervised approach.

Figures 7A-C: (**7A**) Averaged 2D-chromatogram of *Benamaurel* oil samples (field replicates and analytical replicates) obtained at stage 1 and (**7B**) at stage 4. (**7C**) Image comparison results between average image of harvest stage 1 (**7A**) and stage 4 (**7B**). The resulting image is rendered as “colorized fuzzy ratio”. Analytes that varied between stages are listed together wih their unique ID numbering (ref. Table 2).

Table Captions:

Table 1: List of analyzed samples together with plot denomination, field replicate, harvest stage, acronym, quality parameters according to COMMISSION REGULATION (EEC) No 2568/91 of 11 July 1991, sensory evaluation results, and commercial classification.

Table 2: List of the 119 target analytes together with ^{1}D and ^{2}D retention times, I^{T}_{S} and sensory descriptors as reported in reference literature [31,32,33,34,35,36,37,38,39]. The 2D Peak Volume data is provided as Supplementary information in **Supplementary Table 1** - **ST1**.

Table 3: Ripening informative markers evolution trends along harvest stages. The quality of fittings is referred as Coefficient of Determination (R^2).

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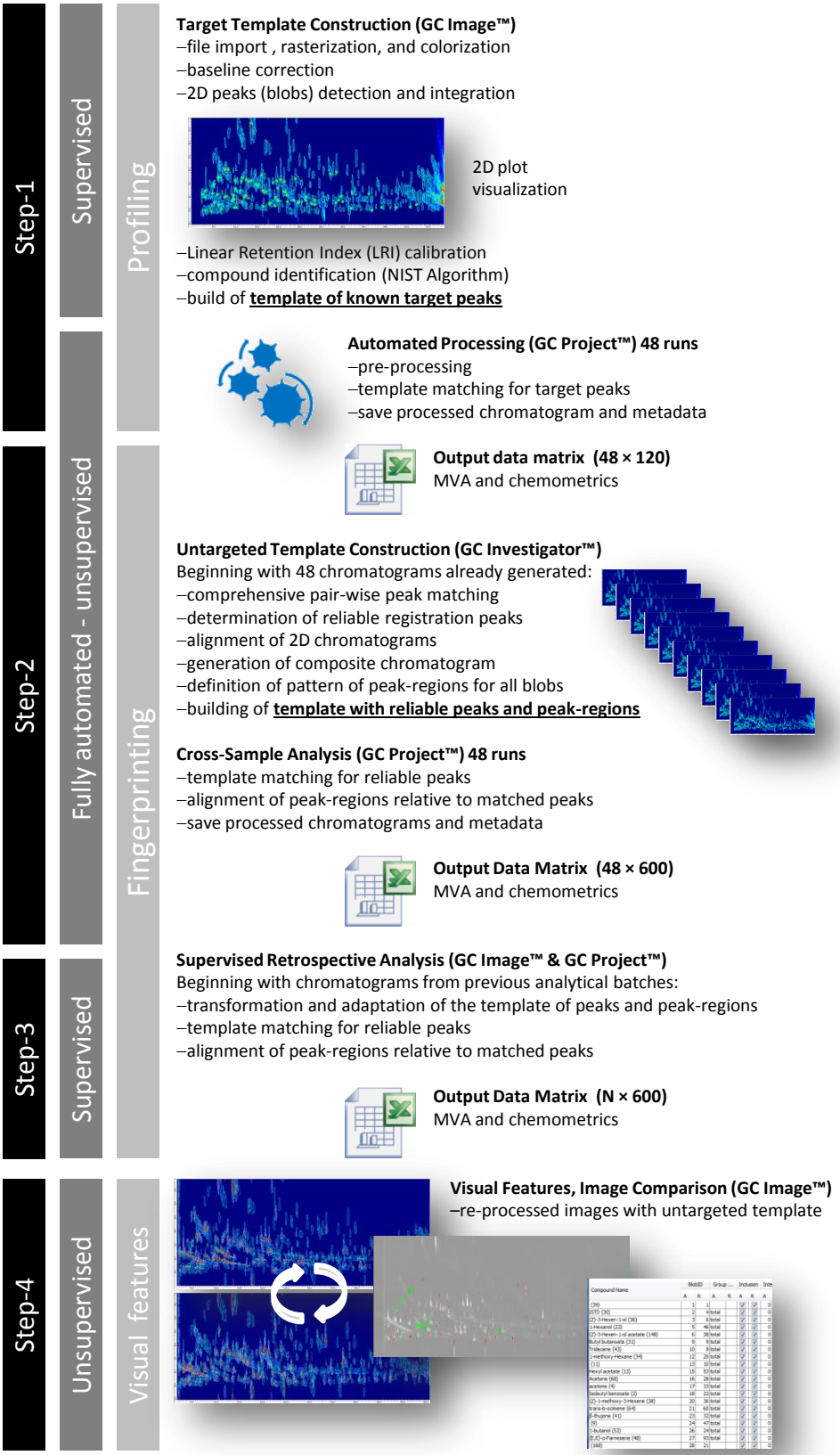

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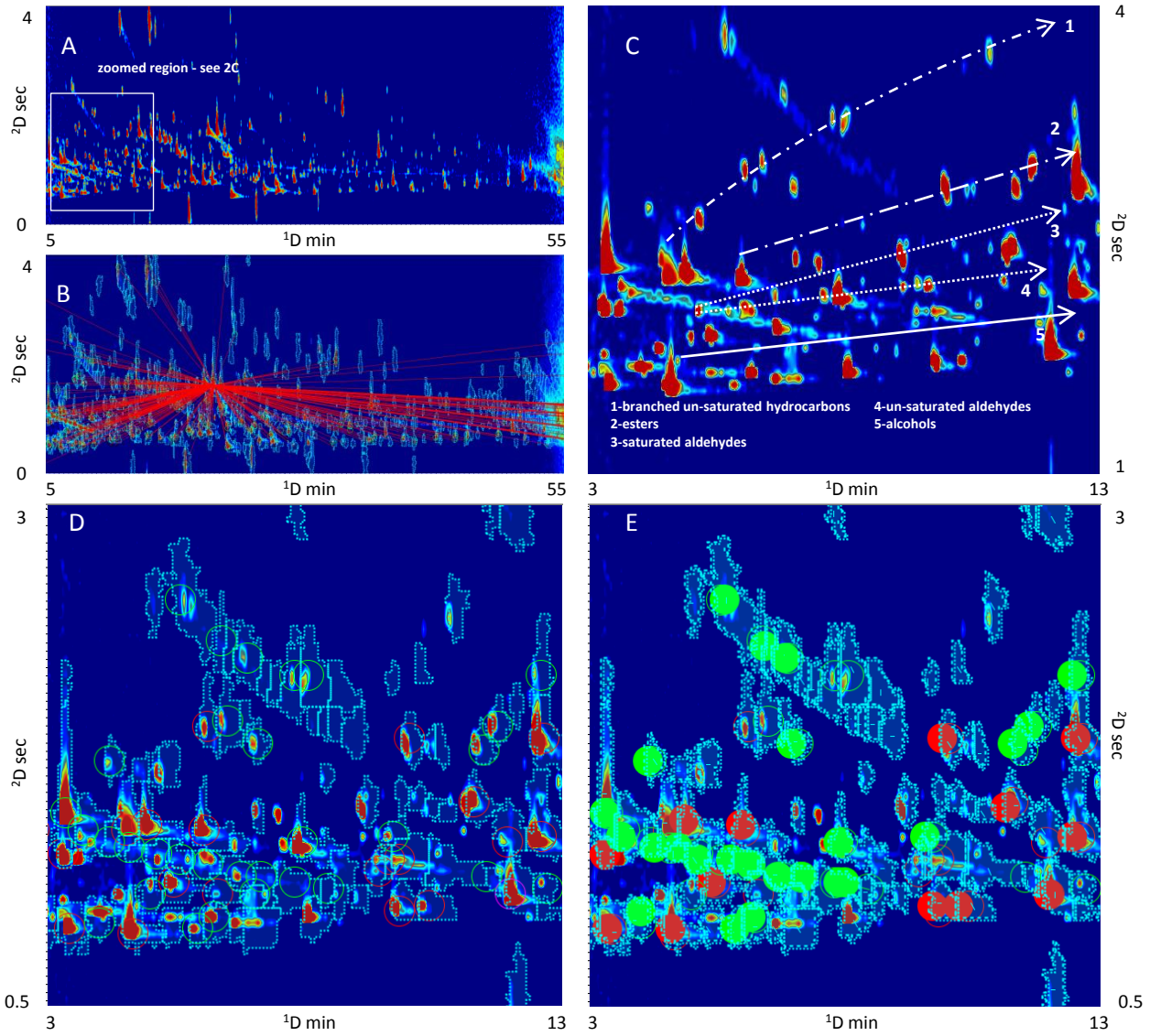

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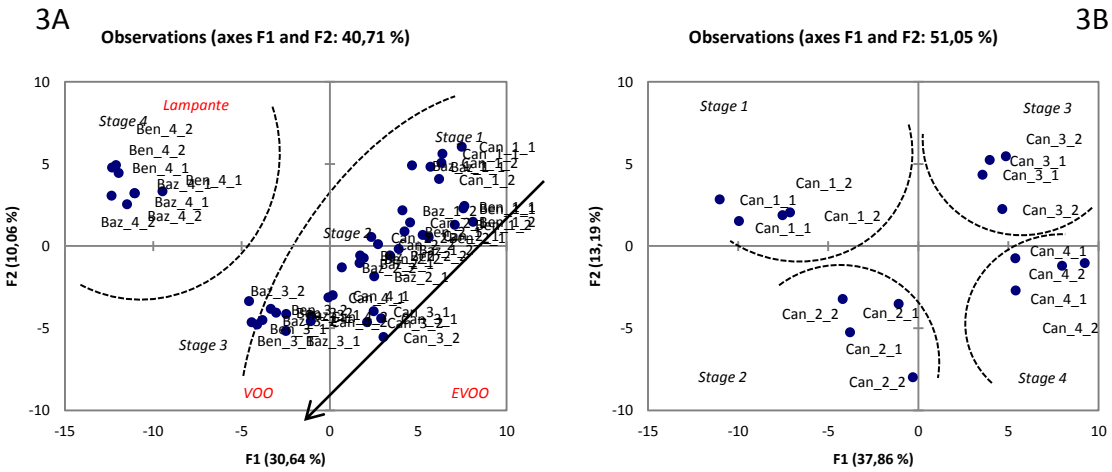

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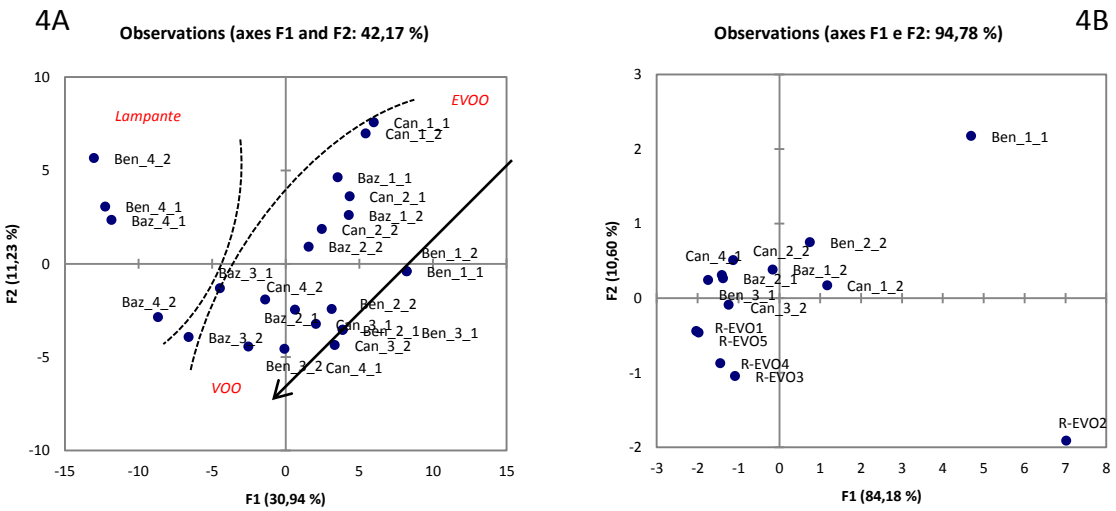

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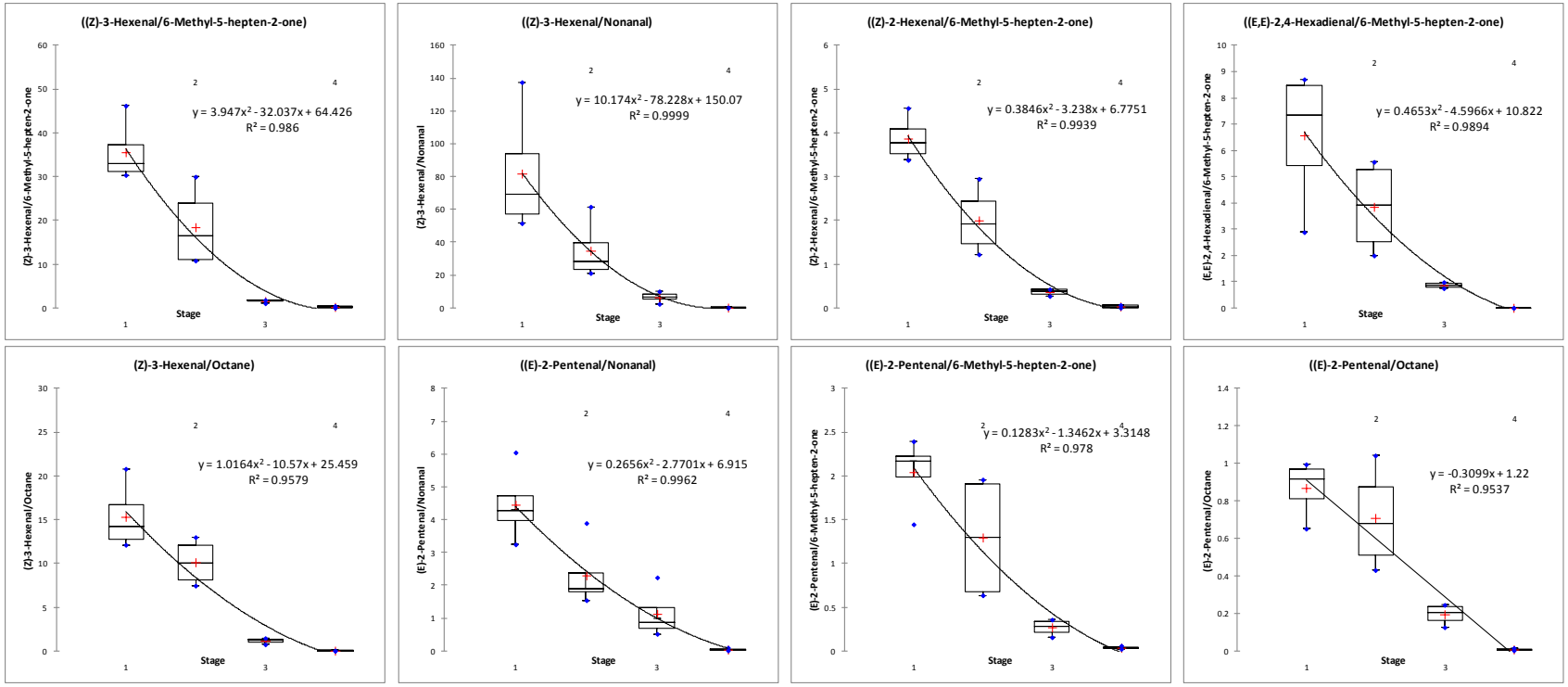

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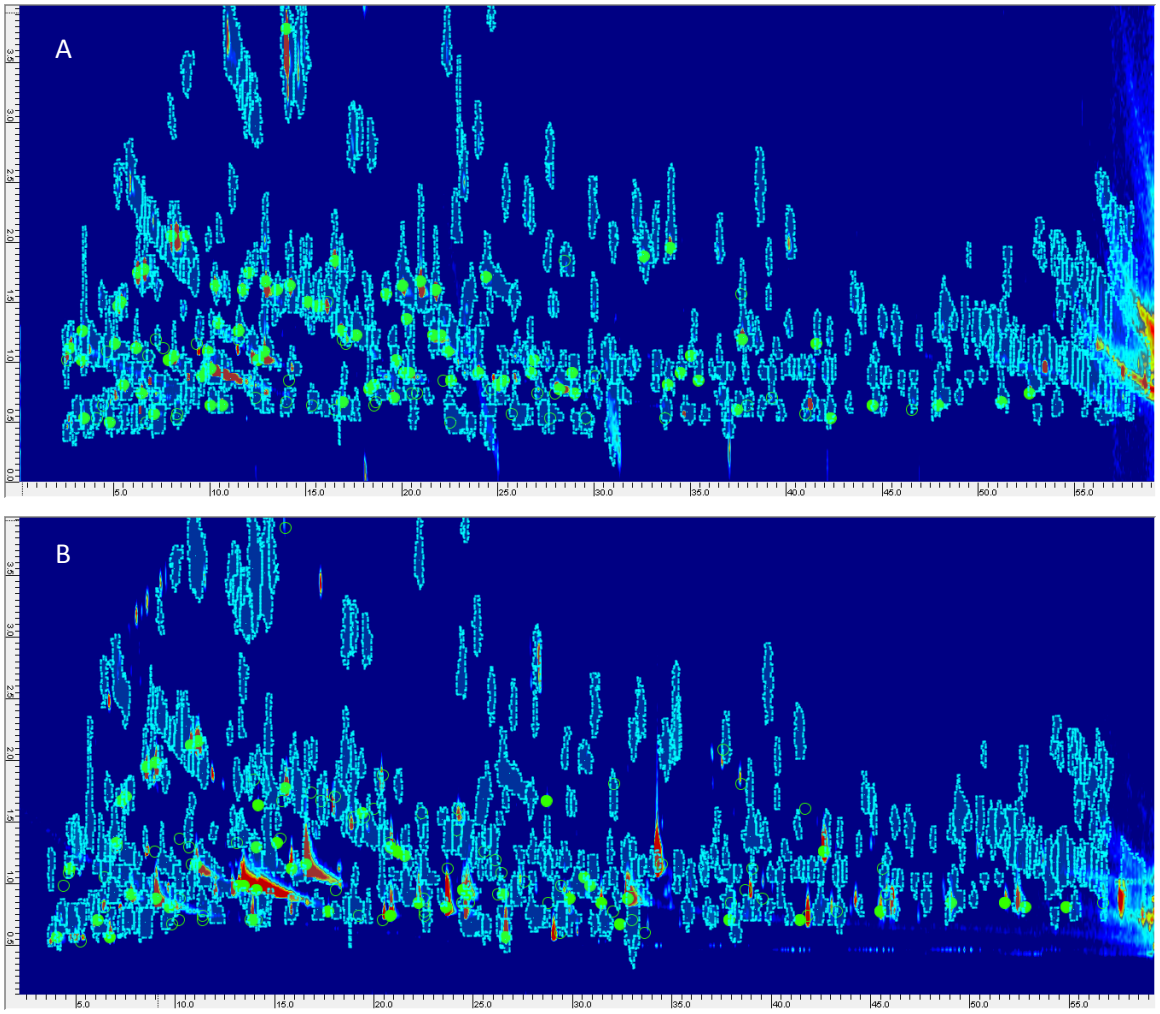

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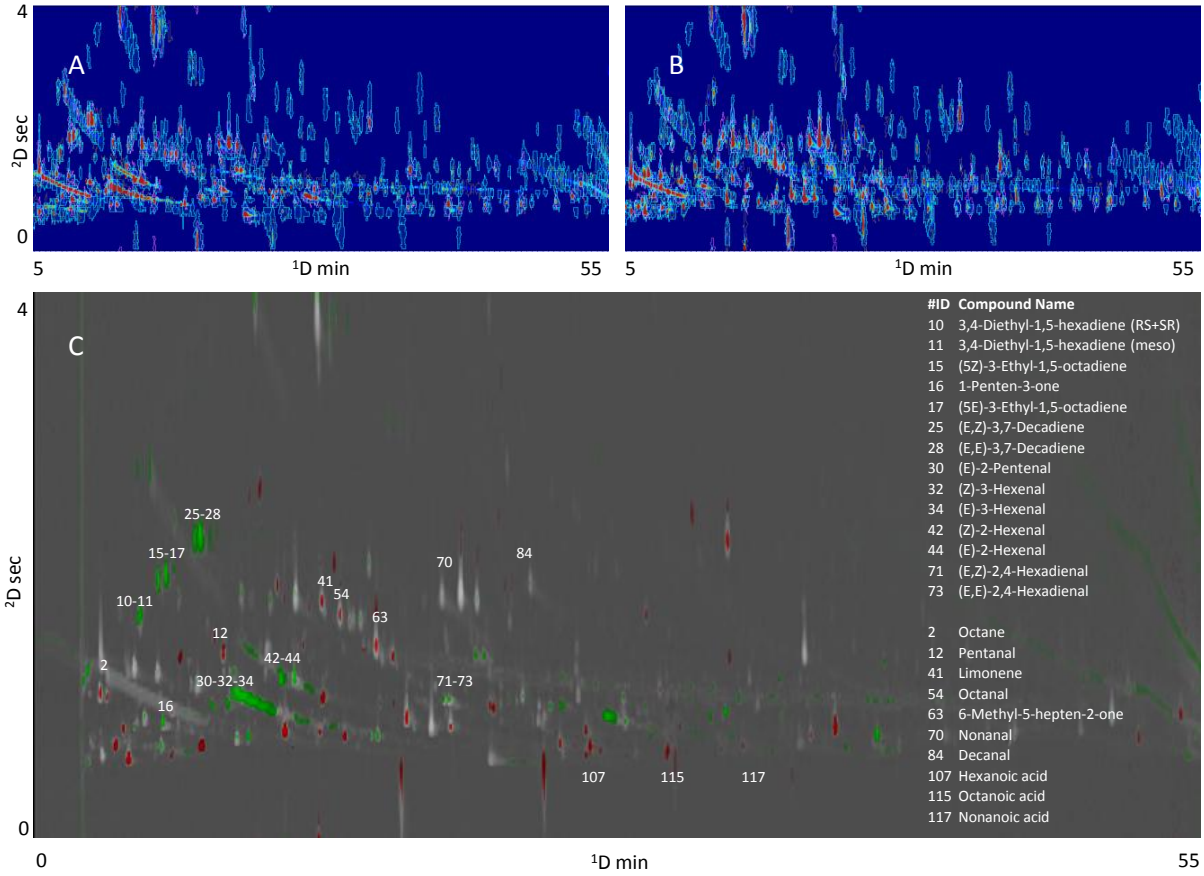

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