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On the use of Ethephon as abscising agent in cv. Crimson Seedless table grape production: Combination of Fruit Detachment Force, Fruit Drop and metabolomics

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Corresponding Author: Dr. Antonino Rizzuti, Ph.D.

Corresponding Author's Institution: Polytechnic of Bari

First Author: Antonino Rizzuti, Ph.D.

Order of Authors: Antonino Rizzuti, Ph.D.; Luis M Aguilera-Saez, Dr; Vito Gallo, Ph.D.; Isabella Cafagna, Ph. D.; Piero Mastrorilli, Prof.; Mario Latronico, Prof.; Andrea Pacifico, Dr; Angela M Matarrese, Dr; Giuseppe Ferrara, Ph.D.

Abstract: The effect of 2-chloroethylphosphonic acid (Ethephon, in the following ETH) as abscising agent on cv. Crimson Seedless table grapes was investigated by means of Fruit Detachment Force (FDF) and Fruit Drop (FD) analyses combined with a metabolomic study carried out by High Resolution Mass Spectrometry (HRMS) and Nuclear Magnetic Resonance (NMR) spectroscopy. The effectiveness of ETH as abscising agent was ascertained with ETH concentration ranging from 1.4 to 4.0 g/L in a two-year study. The ETH treatments caused berry drops higher than 40% and induced an increase of tartaric acid, procyanidin P2, terpenoid derivatives and peonidin-3-glucoside as well as a decrease of catechin and epicatechin. HRMS-NMR covariance analysis was carried out to correlate the fluctuations of tartaric acid NMR signals to those of MS peaks of the secondary metabolites affected by ETH treatments.

**Cover Letter**

**POLITECNICO DI BARI**

**DIPARTIMENTO DI INGEGNERIA CIVILE, AMBIENTALE, DEL TERRITORIO, EDILE E DI CHIMICA**

VIA E. ORABONA, 4 • 70125 BARI (ITALY)

Tel.: +39 0805963607 • Fax: +39 080 5963611

**Dr. Antonino Rizzuti, Ph.D.**

e-mail: antonio.rizzuti@poliba.it

Dear Editor,

please find attached our manuscript entitled:

"**On the use of Ethephon as abscising agent in cv. Crimson Seedless table grapes production: a Combined Study based on Fruit Detachment Force, Fruit Drop and Metabolomics**"

by

*Antonino Rizzuti, Luis Manuel Aguilera-Saez, Vito Gallo, Isabella Cafagna, Piero Mastrorilli, Mario Latronico, Andrea Pacifico, Angela Maria Stella Matarrese, Giuseppe Ferrara*

which we wish to be considered for publication in *Food Chemistry.*

This manuscript reports, for the first time, a study based on the combination of agronomical analyses (Fruit Detachment Force and Fruit Drop) and chemical analyses (Metabolomics carried out by Nuclear Magnetic Resonance spectroscopy and High Resolution Mass Spectrometry) aimed to evaluate the effects of Ethephon (ETH) as abscising agent in *cv.* Crimson Seedless table grapes production.

Along with the metabolomic approach, HRMS-NMR covariance analysis was carried out to gain important information on the effects of Ethephon on primary and secondary metabolite composition. In particular, it was found a correlation between fluctuations of tartaric acid NMR signals and those of MS peaks of the secondary metabolites affected by ETH treatments. These findings give a hint to consider a possible role of tartaric acid in secondary metabolic pathways.

The interest towards ETH application derives from the possibility to produce undamaged single berries suitable for the fresh-cut fruits market.

All the authors have contributed significantly and are in agreement with the content of the manuscript.

The paper is new, not declined by other journals, and it is not being considered for publication elsewhere.

Yours sincerely

Antonino Rizzuti

# On the use of Ethephon as abscising agent in *cv.* Crimson Seedless table grapes production: a Combined Study based on Fruit Detachment Force, Fruit Drop and Metabolomics

Antonino Rizzuti, Luis Manuel Aguilera-Saez, Vito Gallo, Isabella Cafagna, Piero Mastrorilli, Mario Latronico, Andrea Pacifico, Angela Maria Stella Matarrese, Giuseppe Ferrara

## Highlights

NMR and HRMS were used to characterize ETH treated grapes

ETH treatments caused berry drops higher than 40%

ETH treatments increase procyanidins, terpenoid derivatives and peonidin-glu contents

Tartaric acid is involved in senescence processes

*Manuscript
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1 **On the use of Ethephon as abscising agent in *cv.* Crimson Seedless table grapes**
2 **production: a Combined Study based on Fruit Detachment Force, Fruit Drop**
3 **and Metabolomics**

4

5 *Antonino Rizzuti,**[a] *Luis Manuel Aguilera-Saez,*[a] *Vito Gallo,*[a,b] *Isabella Cafagna,*[a] *Piero*
6 *Mastrorilli,*[a,b] *Mario Latronico,*[a,b] *Andrea Pacifico,*[c] *Angela Maria Stella Matarrese,*[c] *Giuseppe*
7 *Ferrara*[c]

8

9 [a] Dipartimento di Ingegneria Civile, Ambientale, del Territorio, Edile e di Chimica, Politecnico di
10 Bari, Via Orabona, 4, I-70125, Bari, Italy
11 [b] Innovative Solutions S.r.l. – Spin off company of Politecnico di Bari, zona H, 150/B, 70015, Noci
12 (BA), Italy
13 [c] Dipartimento di Scienze del Suolo, della Pianta e degli Alimenti, Università degli Studi di Bari
14 "Aldo Moro", Via Amendola 165/A, 70126 Bari, Italy

15

16 * Corresponding author. Tel.: +39 080 5963607; fax: +39 080 5963611.
17 *e-mail address*: antonio.rizzuti@poliba.it

18

19 **Abstract**

20 The effect of 2-chloroethylphosphonic acid (Ethephon, in the following ETH) as abscising agent on
21 *cv*. Crimson Seedless table grapes was investigated by means of Fruit Detachment Force (FDF) and
22 Fruit Drop (FD) analyses combined with a metabolomic study carried out by High Resolution Mass
23 Spectrometry (HRMS) and Nuclear Magnetic Resonance (NMR) spectroscopy. The effectiveness of
24 ETH as abscising agent was ascertained with ETH concentration ranging from 1.4 to 4.0 g/L in a
25 two-year study. The ETH treatments caused berry drops higher than 40% and induced an increase

of tartaric acid, procyanidin P2, terpenoid derivatives and peonidin-3-glucoside as well as a decrease of catechin and epicatechin. HRMS-NMR covariance analysis was carried out to correlate the fluctuations of tartaric acid NMR signals to those of MS peaks of the secondary metabolites affected by ETH treatments.

**Keywords**

Table Grapes; Crimson Seedless; Berry Loosening; Fresh-cut food; High Resolution Mass Spectrometry; Nuclear Magnetic Resonance; Principal Component Analysis; Covariance Analysis; Fruit Detachment Force

## 1. Introduction

Fresh-cut fruits and vegetables are rapidly increasing popularity because of their high quality, attractiveness and numerous nutritional facts, and they are highly practical for a prompt consumption (Çelikkol & Türkben, 2012).

Table grape is a fruit well suited for consumption as fresh-cut product. The most important feature for its acceptance on markets is the lack of defects such as decay, cracking, stem browning, insect damage, grey mould infection and berry softness. Grape quality depends on many factors including pedoclimatic conditions, vineyard treatments, harvest time, cultivar, degree of ripening and phytosanitary conditions. After harvest, table grape undergoes water loss resulting in either stem drying or browning and berry softening. However, long lasting storage of grapes is obtained by post-harvest treatments and by using appropriate packages (Costa et al., 2011).

Italy is one of the greatest world producer and exporter of table grape and Puglia, a region in Southeastern Italy, is the most important Italian region for table grape production. Official data (ISTAT 2012) indicate a table grape cultivation on about 30,000 hectares (60% of the italian area under table grape cultivation), with a yield of 660,000 tons. The economical importance of table grapes worldwide is recognized by the extent of table grapes world market assessed at about 4

52 millions of tons and 5 billions of euros. ‘New countries’, such as Thailand, South Korea, China,
53 Lithuania, are highly requiring table grapes. In this world situation, in 2012, Italian export of table
54 grapes reached 590 million of euros with 482,000 tons, with a mean value of 1.22 €/kg of grape.
55 Besides the traditional buyers of Italian table grapes (Germany, France, UK, Spain), an increasing
56 demand is coming from countries such as Poland, Kingdom of Saudi Arabia and United Arab
57 Emirates. This data suggest also a possible output of table grape as a fresh-cut fruit either to
58 traditional markets (Europe) or to new countries.
59 Fresh-cut products (especially vegetables) are showing an interesting increased consumption in
60 many countries, and it is worth pointing out the remarkable surplus that such products are achieving
61 in terms of commercial value. In these perspectives, table grape as fresh-cut fruit could be sold in
62 supermarkets as well as in vending machines located in schools and offices at a valuable price. In
63 the production of fresh-cut grapes, harvesting is both a time and money consuming part. The
64 application of fruit abscission (loosening) agents can contribute greatly toward enhancing the
65 efficiency of harvesting. In fact, the application of abscission agents decreases the Fruit Detachment
66 Force (FDF) required to separate berries from the stem thus facilitating mechanical harvesting of
67 undamaged individual grape berries (Fidelibus, Cathline, & Burns, 2007). In particular, 2-
68 chloroethylphosphonic acid (ETH), a commercial ethylene-releasing agent used as plant-growth
69 regulator (Brown, 1997), has also been evaluated as a potential fruit loosening agent able to reduce
70 the FDF in a wide range of fruit such as citrus (*Citrus sinensis L.*), grape (*Vitis vinifera L.*)
71 (Christensen, 2000), olive (*Olea europaea L.*), and cherry (*Prunus avium L.)* (Malladi, Vashisth, &
72 Johnson, 2012).
73 The influence of external factors (e.g., growth regulators) on fruit production can be evaluated by a
74 metabolomic approach. Metabolomics aims at measuring the global, dynamic and metabolic response
75 of the living systems to biological stimuli and provides information on a wide range of detectable
76 chemical compounds contained in food products. Metabolomic studies usually involve Nuclear
77 Magnetic Resonance (NMR) spectroscopy or High Resolution Mass Spectrometry (HRMS)

78 supported by multivariate statistical methods (Ali, Maltese, Fortes, Pais, Choi & Verpoorte, 2011;
79 Bevilacqua, Triggiani, Gallo, Cafagna, Mastrorilli & Ferrara, 2012; Ferrara et al., 2013; Ferrara,
80 Mazzeo, Netti et al., 2014; Gallo et al., 2014; Kim, Choi, & Verpoorte, 2010; Nicholson & Lindon,
81 2008; Schripsema, 2010; Wishart, 2008; Son et al., 2009; Sumner, Mendes, & Dixon, 2003). It is
82 generally accepted that a single analytical technique seldom provides complete information on the
83 metabolome and therefore a combined approach is desirable to gain a comprehensive view. In this
84 respect, combination of NMR with HRMS is advisable as NMR easily provides information on
85 molecules with relatively high concentration (typically, such molecules correspond to primary
86 metabolites) while HRMS supplies precious information on molecules at low concentration
87 (typically, such molecules constitute secondary metabolites) (Aliferis & Jabaji, 2010 Rizzuti,
88 Caliandro, Gallo, Mastrorilli, Chita, & Latronico, 2013). Recently, our research has been focused on
89 the evaluation of the effects of various plant-growth regulators on the metabolic profiles of table
90 grapes. The positive effect of S-ABA on skin colour of *cv*. Crimson Seedless was ascertained,
91 without any significant change in the profile of the primary metabolites (Ferrara et al., 2013).
92 Moreover, the effects of gibberellic acid ($GA_3$) and 1-(2-chloropyridin-4-yl)-3-phenylurea
93 (forchlorfenuron, CPPU) on amino acids composition of *cv*. Italia (Ferrara, Mazzeo, Matarrese et
94 al., 2014) have been established.
95 In the present study, application of ETH on *cv*. Crimson Seedless was investigated with the aim to
96 verify its effectiveness as abscising agent for producing undamaged single berries suitable for the
97 fresh-cut fruits market. Furthermore, the effect of ETH on metabolic profile was evaluated by
98 combination of NMR and HRMS measurements that were correlated to the Fruit Drop (FD) and
99 Fruit Detachment Force (FDF) values.
100

101 **2. Materials and Methods**

102 All chemicals were of analytical reagent grade. Sodium hydroxide, sodium azide and formic acid
103 were purchased from Sigma Aldrich (Milan, Italy). Acetonitrile, and methanol LC/MS grade and

104 isopropanol HPLC grade were purchased from VWR (Milan, Italy). Water was doubly deionised
105 (resistivity: 18 MΩ·cm) with a Milli-Q water purification system (Merck Millipore, Darmstadt,
106 Germany).
107
108 *2.1 Fruit materials and sample preparation*
109 Table grape samples of *cv*. Crimson Seedless were collected for two consecutive years (2010 and
110 2011) in vineyards located in the countryside of Adelfia and Acquaviva delle Fonti, in the province
111 of Bari (Puglia region). Vines were spaced 2.8 × 2.5 m, trained to an overhead trellis system with 5-
112 6 fruiting canes/vine and drip irrigated (3,000-3,200 $m^3$/ha). Fertilizer additions, pest control and
113 other vineyard operations (berry thinning, leaf removal, and lateral shoots thinning) were conducted
114 according to local practices. A randomized block design was used with three blocks and three
115 treatments, and each treatment in the block consisted of three grapevines selected for uniform
116 vigour and with a similar crop load. The bunches were treated with increasing amount of ETH.
117 During 2010, samples were submitted to ETH concentrations of 1.4 and 3.0 g/L (10T1 and 10T2,
118 respectively) and compared with the control samples (10CTRL), while during 2011, 3.0 and 4.0 g/L
119 (11T2 and 11T3, respectively) of ETH were used and the treated grapes were also compared with
120 control samples (11CTRL). In 2010, ETH was applied on the $19^{th}$ of September and the grapes were
121 harvested on the $5^{th}$ of October, whereas in 2011 ETH treatment was performed on the $23^{rd}$ of
122 September and harvest was done on the $7^{th}$ of October. The bunches were sprayed by using a
123 manual pump with care to wet whole bunches only when the fruits reached sufficient soluble solids
124 content (at least 16 °Brix). After treatments, bunches were wrapped by a plastic net in order to
125 collect berries dropping from pedicel before harvesting (see Figure 1). At harvest, the bunches were
126 collected and carried to the laboratory in a thermal bag at 8-10 °C. Bunches were manually shaken
127 and abscised berries were collected in order to be visually checked for integrity of (dry) stem scar
128 and for the presence/absence of the pedicel. Fruit drop percentage was calculated as FD% =
129 [(DB+SB)/TB]*100 where DB represents the weight of the berries spontaneously dropped into the

130 plastic net before harvest, SB represents the weight of the berries dropped after shaking of the
131 bunches in the laboratory and TB represents the total weight of the bunch (sum of DB, SB and the
132 weight of the berries still attached to the rachis). FDF measurements were performed on the berries
133 still attached to the rachis by means of a mechanical detachment gauge (Somfy Tec, France).
134 Detached grape berries were stored at −20 °C until NMR and HRMS analyses. Before sample
135 preparation, berries were defrosted for 40 minutes, then they were squeezed and centrifuged (15
136 min and 4000 rpm at room temperature) to obtain juices for NMR and HRMS measurements.
137
138 *2.2 High Resolution Mass Spectrometry*
139 100 μL of centrifuged juice was added to 1.0 mL of a solution containing $CH_3OH$, $H_2O$, HCOOH
140 (in the volume ratio 70:30:1, respectively) and 30 μg of $NaN_3$. Fifteen replicates were prepared for
141 each treatment.
142 Liquid chromatography was carried out with an Agilent High Performance Liquid Chromatography
143 (HPLC) system (Agilent, Milan, Italy), equipped with a vacuum degasser (G1322A, Agilent), an
144 autosampler (G1377A, Agilent), a quaternary pump and a thermostated column department, a
145 reversed-phase $C_{18}$ analytical column (HDB, 4.6 x 150 mm, particle size 5 μm, Agilent) protected
146 by a guard cartridge of the same packing, and maintained at 25 °C. The HPLC device was
147 connected online to a MicrOTOF-Q II mass spectrometer (Bruker Daltonik GmbH, Bremen,
148 Germany) equipped with an Electrospray Ionization Source (ESI). The injection volume of the
149 samples was 20 μL. The mobile phase, consisting of water with formic acid (0.1%) (A) and
150 acetonitrile with formic acid (0.1%) (B), was pumped at 1.0 mL/min into the HPLC system with the
151 following gradient elution program: 0-3 min, isocratic 95% A; 3-18 min, linear from 5 to 95% B;
152 18-20 min, isocratic 95% B; 20-21 min, linear from 95 to 5% B; 21-25 min, isocratic 5% B. A
153 divert valve was used to remove substances (mainly polar primary metabolites) eluting during the
154 initial three minutes thus allowing detection of the less polar part mainly consisting of secondary
155 metabolites. The Time-Of-Flight (TOF) detector, used for accurate mass measurements, operated in

156 both negative (nebulizer gas, nitrogen, 4 bar; dry gas, nitrogen, 10 L/min, 200 °C; endplate offset
157 −500 V; capillary voltage +3.5 kV; mass range 50-1000 *m/z*) and positive (nebulizer gas, nitrogen,
158 4 bar; dry gas, nitrogen, 10 L/min, 200 °C; endplate offset −500 V; capillary voltage −4.5 kV; mass
159 range 50-1000 *m/z*) mode. External calibrations were made using a 100 L KD Scientific syringe
160 pump with a reference solution made up of 10 μL of formic acid (98%), 10 μL of aqueous sodium
161 hydroxide (1.0 M), 490 μL of *i*-propanol and 490 μL of deionized water. The raw-file data were
162 collected as continuum mass spectra at a regular time interval (spectra rate of 1 spectrum/s with a
163 rolling averages of 3). Mass spectra were processed using Data Analysis 4.0. The SmartFormula
164 tool within DataAnalysis$^{TM}$ (Bruker Daltonik GmbH, Bremen, Germany) was used to obtain the
165 elemental composition, errors and sigma values for each detected compounds. MS data were
166 assigned to metabolites on the bases of accurate mass, isotopic distribution and fragmentation
167 pattern in both positive and negative ion modes. Assignments were confirmed after comparison
168 with literature data (Cantos, Espín, & Tomás-Barberán, 2002; Cavaliere, Foglia, Gubbiotti,
169 Sacchetti, Samperi & Laganà, 2008; Cejudo-Bastante, Pérez-Coello, & Hermosín-Gutiérrez, 2010;
170 Flamini, 2013; Godevac, Teševic, Veličković, Vujisica, Vajs & Milosavljević, 2010; Gollücke,
171 Catharino, de Souza, Eberlin, & de Queiroz Tavares, 2009; Gómez-Romero, Zurek, Schneider,
172 Baessmann, Segura-Carretero & Fernández-Gutiérrez, 2011; Gómez-Romero, Segura-Carretero, &
173 Fernández-Gutiérrez, 2010; Guerrero et al., 2009; He et al., 2010; Kajdžanoska, Gjamovski, &
174 Stefova, 2010; Kneknopoulos, Skouroumounis, Hayasaka, & Taylor, 2011; Moco et al., 2006;
175 Rodríguez-Medina, Segura-Carretero, & Fernández-Gutiérrez, 2009; Sonni, Clark, Prenzler, Riponi,
176 & Scollary, 2011; Sonni, Moore, et al., 2011; Stalmach, Edwards, Wightman, & Crozier, 2011;
177 Stefova & Ivanova, 2011) and with on-line public metabolite databases (PubChem
178 <http://pubchem.ncbi.nlm.nih.gov/>, Metlin <http://metlin.scripps.edu/> and Chemspider
179 <http://www.chemspider.com>). Mass data for statistical analysis were generated by bucketing
180 procedures of the mass spectra. Bucketing was performed using AMIX 3.9.13 software
181 (BrukerBioSpin GmbH, Rheinstetten, Germany) applying the advanced bucketing mode with a *m/z*

182 displacement of 0.03 in the range of 50.50 and 1000.50 Da, and scaling the intensities of individual
183 ions to total intensity recorded between 3.25 and 10.75 min. The buckets were used as variables for
184 Principal Component Analysis (PCA) executed by AMIX 3.9.13.
185
186 *2.3 Nuclear Magnetic Resonance*
187 500 μL of centrifuged juice were added to 300 μL of 0.15 $\%_w$ sodium salt of
188 (trimethylsilyl)propionic-2,2,3,3-$d_4$ acid (TSP) in $D_2O$, 200 μL of oxalate buffer pH = 4.2 [pH value
189 was reached after addition of 37% HCl to 100 mL of an aqueous solution containing $Na_2C_2O_4$ (0.25
190 M) and $NaN_3$ ($2.5 \cdot 10^{-3}$ M)]. Fifteen replicates were prepared for each treatment.
191 One-dimensional $^1$H NOESY spectra were recorded on a Bruker Avance I 400 MHz spectrometer
192 equipped with a 5 mm inverse probe and with an autosampler. $^1$H NOESY spectra were acquired
193 with 128 scans of 64 K data points with a spectral width of 8013 Hz, a pulse angle of 90°, an
194 acquisition time of 4.09 s, a mixing time of 10 ms and a recycle delay of 3.0 s. Each spectrum was
195 acquired using TOPSPIN 3.0 software (Bruker BioSpin GmbH, Rheinstetten, Germany) under an
196 automatic procedure lasting approximately 22 min and consisting of sample loading, temperature
197 stabilization for 5 min, tuning, matching, shimming and 90° pulse calibration. Free induction decays
198 (FIDs) were Fourier transformed, the phase was manually corrected, the baseline was automatically
199 corrected and the spectra were aligned by setting the TSP singlet to 0 ppm. NMR raw data were
200 processed using TOPSPIN 3.0 and, unless otherwise stated, converted in regular rectangular
201 buckets (0.04 ppm width) by AMIX 3.9.13. Multivariate statistical analysis of NMR data were
202 performed using the AMIX 3.9.13.
203
204 *2.4 Covariance analysis*
205 The correlation among NMR and HRMS data vectors were studied by calculating the covariance
206 matrix:

$$COV_{AB}(i,j)=\sum_k \left(\hat{y}_k(i)-\langle\hat{y}(i)\rangle\right)_A \left(\hat{y}_k(j)-\langle\hat{y}(j)\rangle\right)_B$$
207

208 where A and B stand for NMR and HRMS, respectively, $\hat{y}_k(i)$ is the pre-processed bucket of
209 sample $k$ and $\langle\hat{y}(i)\rangle$ is the average value calculated over the samples for the $i$-th variable.
210 Calculation of the covariance matrix was performed using AMIX 3.9.13 with NMR and HRMS
211 buckets generated in the advanced bucketing mode. The resulting covariance matrix was submitted
212 to the combined covariance tool in AMIX 3.9.13.
213

214 **3. Results and discussion**

215 *3.1 Fruit Drop and FDF analyses*

216 The effect of ETH on fruit drop of treated bunches was significant in both 2010 and 2011 years.
217 Berries abscised after the treatment with ETH presented a dry, corky scar at the abscission zone
218 (pedicel/fruit interface) (Figure S1).
219 During 2010, drop of berries ranged from 40% (10T1) to 59% (10T2) for ETH treated grape
220 whereas fruit drop of control berries was almost absent (Figure S2a). FDF measurements on berries
221 still attached to the rachis indicated that untreated grapes were found slightly more resistant
222 (10CTRL: 8.06 ± 2.07 N) with respect to treated ones (10T1: 6.16 ± 2.71 N; 10T2: 6.50 ± 2.48 N).
223 No significant difference derived from the two concentrations of ETH used in the treatments.
224 During 2011, the percentage of berry drop following the application of ETH was comparable to
225 values recorded in 2010 and was not different for the two treatments (11T2: 42%; 11T3: 46 %).
226 Fruit drop value of control berries was again very low. FDF values measured for control grapes
227 (11CTRL: 7.94 ± 2.08 N) were similar to those recorded for treated grapes (11T2: 8.04 ± 1.78 N;
228 11T3: 7.69 ± 1.70 N) (Figure S2b).
229 In all cases, detached berries showed dry stem scars which is a positive and desired response,
230 especially in the view of a possible use of 'Crimson Seedless' berries as fresh-cut fruits. In general,

231 ETH treatments were effective, even at the lowest concentration of 1.4 g/L to abscise around 40%

232 of berries by simple shaking.

233

234 *3.2 Analysis of HRMS spectra*

235 HRMS analysis permitted the identification of 43 compounds belonging to several metabolite

236 classes including alcohols, organic acids, phenolic acids (hydroxybenzoic and hydroxycinnamic

237 acids), amino acid derivatives, flavonoids (flavanols, flavones and anthocyanins) and terpenoid

238 glycosides. The lists of detected metabolites are reported in table 1 (detection in negative mode) and

239 table S1 (detection in positive mode).

240 As shown in Tables 1 and S1, different phenolic compounds such as flavonols, flavanols,

241 anthocyanins, hydroxybenzoic and hydroxycinnamic acids were identified by HRMS analysis. Such

242 metabolites are considered healthy compounds due to their antioxidant activities (Flamini, 2013)

243 and they constitute an added value for table grapes used as fresh-cut fruit products. Anthocyanins

244 found in our grapes were only peonidin, petunidin and delphinidin glucosides. In fact, Crimson

245 Seedless has a relatively low concentration of total anthocyanins (100-200, mg/kg of fresh weight)

246 with respect to other red table grape cultivars, with the predominant anthocyanin being peonidin-3-

247 glucoside (66-85% of the measured anthocyanins) (Cantos et al., 2002; Ferrara, Mazzeo, Netti et al.,

248 2014).

249 Glutathionyl caftaric acid and indole-3-lactic acid hexose were the metabolites that gave the most

250 intense peaks. Glutathionyl caftaric acid is produced rapidly by the enzymatic oxidation of the

251 caftaric acid due to the crushing of the grape berries during the preparation of the samples

252 (Singleton, Salgues, Zaya, & Trousdale, 1985). Indole-3-lactic acid hexose is a metabolite deriving

253 from the tryptophan de-amination pathway which leads ultimately to indole-3-acetic acid (IAA)

254 formation. IAA is the most abundant member of the auxin class of plant hormones and represents

255 the inhibitor of ripening most studied for non-climacteric fruits such as grapes.

256

257 *3.2.1 PCA applied to HRMS data*

258 PCA was performed in order to find possible grouping of grape samples as a consequence of ETH
259 treatments. Figure 2 shows PC1/PC2 *scores* and *loadings* plots obtained for grape samples
260 harvested during 2010 and analysed by HRMS(–). The *scores* plot (Figure 2a) indicates that grape
261 samples are differentiated into three groups with PC1 explaining 32.7% and PC2 15.6 % of the total
262 variance. As ascertained by PC1/PC2 *loadings* plot (Figure 2b), the discriminating metabolites
263 along PC1 were procyanidin P2 (*m/z* 577.1501), procyanidin C1 (*m/z* 865.2238), indole-3-lactic
264 acid hexose and its $[2M\text{-}H]^-$ adduct (*m/z* 366.1288 and 733.2681), benzyl alcohol hexose-pentose
265 (*m/z* 401.1560) and coumaric acid hexose (*m/z* 325.0960). In particular, samples 10T2 were
266 characterized by a higher amount of procyanidins whereas indole-3-lactic acid hexose, benzyl
267 alcohol hexose-pentose and coumaric acid hexose were found in larger amounts in 10T1 and
268 10CTRL samples.

269 Along PC2, samples 10CTRL were differentiated from 10T1 and 10T2 due to higher content of
270 catechin/epicatechin (*m/z* 289.0779), glutathionyl-catechin compounds (*m/z* 594.1559) and
271 coumaric acid hexoses (*m/z* 325.0960 and 145.0313). Moreover, 10T1 and 10T2 samples contained
272 higher amount of tetrahydroabscisic acid hexose (*m/z* 429.2192), dihydrophaseic acid hexose (*m/z*
273 443.2038), peonidin-3-O-glucoside (*m/z* 461.1221), dihydroisorhamnetin hexoside (*m/z* 479.1316),
274 myricetin derivative (*m/z* 481.1436), glutathionyl caftaric acid (*m/z* 616.1378) and glutathionyl
275 caffeic acid derivative (*m/z* 646.17395).

276 The reduction of catechin/epicatechin as a consequence of ETH application is probably the result of
277 the condensation of such flavanols, a clear symptom of ageing ('senescence') of the berry. This
278 hypothesis is substantiated by the increase of procyanidin P2 and C1 (flavanols dimers) and of
279 terpenoid derivatives such as dihydrophaseic acid hexose in treated berries. Dihydrophaseic acid
280 (DPA) is an abscisic acid (ABA) catabolite (Owen, Lafond, Bowen, Bogdanoff, Usher & Abrams,
281 2009), which can suggest that large quantities of ABA had been produced and catabolized in the
282 berry due to treatments with ETH, even though such treatments occurred at late stages. High

283 amounts of peonidin-3-O-glucoside in treated samples are in agreement with literature data
284 indicating that peonidin-3-glucoside content significantly increased after ETH application to
285 Crimson Seedless grapes (Human & Bindon, 2008).
286 PC1/PC2 *scores* and *loadings* plots obtained by mass data acquired in positive ion mode
287 [HRMS(+)] are shown in figures S3a and S3b, respectively. In this case, 10CTRL, 10T1 and 10T2
288 samples were differentiated along the PC1 (explaining 22.8% of the total variance) mainly due to
289 anthocyanin peonidin-3-O glucoside at *m/z* 463.1292 which was found in larger amount in the 10T2
290 samples and to indole-3-lactic acid hexose at *m/z* 385.1638 (in the form of its ammonia adduct),
291 found in larger amount in the 10CTRL samples. These results confirm those obtained with PCA
292 applied to HRMS(–) data.
293 In 2011 Crimson Seedless samples were treated using an ETH concentration of 3.0 g/L and 4.0 g/L.
294 In order to have a correspondence of ETH concentration with treatments carried out in 2010,
295 samples treated with 3.0 g/L will be indicated with 11T2 while samples treated with 4.0 g/L of ETH
296 will be denoted as 11T3. PCA applied to HRMS data of 11CTRL, 11T2 and 11T3 samples
297 indicated a lower grouping of the grapes thus suggesting that, during 2011, ETH treatments had a
298 lower influence on their metabolic profiles. These findings match those described above for FDF
299 and FD analyses.
300
301 *3.3 Analysis of NMR spectra*
302 $^{1}$H NMR spectra of table grape samples collected during 2010 and 2011 allowed for straightforward
303 identification of primary metabolites, namely sugars, organic acids and amino acids.
304 In Figure S4, a typical spectrum of 'Crimson Seedless' berries is shown. In the portion between
305 10.0 and 6.0 ppm very weak signals attributable to phenolic and aromatic compounds are present.
306 The most intense signals, in the region from 6.0 to 2.5 ppm, are attributable to glucose, fructose,
307 tartaric acid and malic acid. In the region 2.5-0.0 ppm most signals derive from amino acids.
308 Signals attribution was made by comparison with spectra of authentic samples and with literature

309 data (Ali et al., 2011; Ferrara et al., 2013; Ferrara, Mazzeo, Netti et al., 2014; Gallo et al., 2014; Son
310 et al., 2009).
311 In Table 2, metabolites identified in berries of 'Crimson Seedless' are listed and, for each signal,
312 chemical shift (δ, ppm) and multiplicity are also reported.
313
314 *3.3.1 PCA applied to NMR data*
315 PCA applied to NMR data (generated by regular bucketing of the whole spectrum) indicated no
316 substantial effects of the treatments on the primary metabolite profile of the grapes. In fact, for each
317 year, scores of the treated samples were superimposable to those of control grapes. Considering
318 both 2010 and 2011 production years, samples were clearly discriminated on the basis of the
319 harvest, thus confirming that pedo-climatic conditions had a greater discriminating effect on the
320 primary metabolites with respect to the treatments.
321 A deeper inspection of NMR spectra indicated that effects of the treatments could be appreciated,
322 for samples collected during 2010, when only signals belonging to the organic acids (tartaric, malic
323 and citric), proline and ethanol were considered. Thus, PCA was applied to variables generated by
324 integration of NMR signals of such metabolites.
325
326 Figure 3 shows PC1/PC2 *scores* and *loadings* plots obtained for samples collected during 2010.
327 *Scores* plot indicates that the three groups of grapes (10CTRL, 10T1, 10T2) are differentiated each
328 other along PC1, which explains 75.2 % of the total variance. Control samples are located at
329 positive PC1 values and treated samples move towards negative PC1 values as an effect of the
330 increasing ETH concentration. As ascertained by *loadings* plot, the species mainly responsible for
331 such a discrimination is tartaric acid.
332 NMR data related to samples collected during 2011 do not indicate substantial effects of ETH
333 treatments on metabolic profiles of the grapes.
334

335 *3.4 HRMS-NMR covariance analyses*

336 It is known that application of ETH has no important effects on soluble solid content, total acidity,
337 pH, yield and berry weight whereas it affects composition of secondary metabolites (Szyjewicz,
338 Rosner & Kliewer, 1984). Our findings are in agreements with these results as indicated by NMR
339 for primary metabolites and by HRMS for secondary metabolites. Anyway, the dependence of
340 tartaric acid on ETH treatments for grapes harvested during 2010 raises the question whether ETH
341 affect the ripening level of the grapes or only metabolic pathways leading to berry senescence.
342 Tartaric acid biosynthesis begins with L-ascorbic acid (differently from other fruit acids), in
343 particular with the cleavage of a six-carbon intermediate between C4/C5 thus yielding tartaric acid
344 and glycoaldehyde (DeBolt, Cook & Ford, 2006). In our case, the application of ETH may stimulate
345 the catabolism of ascorbic acid (AA) thus leading to an increase of tartaric acid biosynthesis, since
346 ethylene stimulates plant senescence and consequently reduction of AA in leaves (Bartoli,
347 Simontacchi, Montaldi & Puntarulo, 1996) and probably in other plant organs. One of the most
348 important changes observed during plant senescence is the decline in antioxidant contents and the
349 increase in the steady state of reactive oxygen species and a reduction of AA is considered very
350 important for the plant antioxidant defence (Gergoff, Chaves & Bartoli, 2010). The decreases of AA
351 may be the consequence of ETH effect on either reducing the biosynthesis or on increasing the
352 degradation through reactions possibly leading to a slight increase of tartaric acid in the berry.

353 In order to find a possible link between tartaric acid and the secondary metabolites affected by ETH
354 treatments, HRMS-NMR covariance analysis was carried out. Covariance analysis indicates signals
355 belonging to metabolites characterized by correlated fluctuations of their intensities. Correlations
356 are positive when the metabolite content distributions are coherent and negative when the
357 metabolite content distributions are opposite.

358 Figure 4 shows the results obtained by correlation of NMR spectra with HRMS spectra recorded in
359 negative (Figure 4a) and positive ion mode (Figure 4b) for samples collected during 2010. Tartaric
360 acid is positively correlated to peonidin-3-O-glucoside, dihydroisorhamnetin hexoside and

361 procyanidin P2 and is negatively correlated to catechin/epicatechin, coumaric acid hexose, indole-3-
362 lactic acid hexose, indole-3-lactic acid hexose adduct, benzyl alcohol hexose-pentose, glutathionyl
363 catechin, glutathionyl caftaric acid and indole-3-lactic acid hexose adduct.
364 In other words, tartaric acid is positively correlated to compounds which were found more abundant
365 in ETH treated samples and is negatively correlated to compounds characterizing control grapes.
366 Variation of the tartaric acid concentration could be associated to possible different ripening levels
367 of the grapes as an effect of ETH treatments. Actually, this is not the case. In this regard, it must be
368 considered that ripening of the grapes is characterized by an increase of sugar amounts and a
369 concomitant decrease of organic acids concentrations, especially tartaric acid. However, a recent
370 work on Arabidopsis and spinach leaves showed that leaf AA biosynthesis and content is down-
371 regulated by ethylene application (Gergoff et al., 2010) and AA is the key component for tartaric
372 acid biosynthesis (DeBolt et al., 2006). Since NMR signal intensities of sugars were unaltered by
373 ETH treatments and since tartaric acid was correlated to metabolites characterizing ETH treated
374 samples, it can be concluded that ETH application at late stages does not affect ripening level of the
375 grapes and tartaric acid is somehow involved in secondary metabolic pathways (as in leaves) which
376 deserve deeper investigations.
377

378 **4. Conclusions**

379 This study demonstrates that ETH is an effective abscising agent giving satisfactory results in terms
380 of berry drop ranging from 40% to 59% during 2010 and from 42% to 46% during 2011.
381 Considering that Crimson Seedless is a cultivar unaffected by shatter problems, application of ETH
382 to cultivars with shatter problems could be expected to increase the drop percentage. Moreover,
383 drop percentages obtained in our study encourages a possible use of Crimson Seedless as fresh-cut
384 fruit.
385 As usual in horticultural studies, also in our case different results were obtained for each year. In
386 particular, effects of ETH applications on FDF values and on metabolic profile were more

387 pronounced during 2010. Concerning primary metabolite composition, tartaric acid content was
388 found slightly higher in ETH treated grapes. Among the secondary metabolites, accumulation of
389 procyanidins and terpenoid derivatives in the treated samples indicated that senescence processes
390 are favored by ETH.

391 Finally, HRMS-NMR covariance analysis allowed to correlate NMR tartaric acid signal to mass
392 peaks of secondary metabolites discriminating ETH treated samples. Moreover, such covariance
393 study indicated that the variations of tartaric acid quantities in the grapes are related to ETH
394 treatments and are not due to possible different ripening levels.

395

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400

401 **Appendix A. Supplementary data**

402 Supplementary data associated with this article can be found, in the online version, at http:

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# Tables

**Table 1.** Peak assignment of the metabolites found in ‘Crimson Seedless’ berries using HRMS in the negative-ion mode.

| *Peak label** | *Retention Time [min]* | *$[M-H]^-$ m/z* | *Fragments or adducts formed in the MS source* | *MS/MS ions* | *Error (mDa)* | *mSigma Value* | *Formula $[M-H]^-$* | *Compound* |
|---|---|---|---|---|---|---|---|---|
| *Alcohols and derivatives* | | | | | | | | |
| 1 | 3.25 | 383.1560 (100) | - | - | -3.0 | 33.5 | $C_{15}H_{27}O_{11}$ | 2,3-Butanediol pentoside hexoside |
| 20 | 7.67 | 431.1613 (100) | - | - | -5.3 | 3.3 | $C_{19}H_{27}O_{11}$ | Benzyl alcohol dihexose |
| 27 | 8.13 | 401.1508 (100) | 269.1061 (2) | - | -5.4 | 8.9 | $C_{18}H_{25}O_{10}$ | Benzyl alcohol hexose-pentose |
| 31 | 8.29 | 415.1663 (100) | - | | -5.3 | 24.7 | $C_{19}H_{27}O_{10}$ | Benzyl alcohol disaccharide derivative |
| 38 | 8.77 | 415.1675 (100) | - | - | -6.4 | 13.7 | $C_{19}H_{27}O_{10}$ | Benzyl alcohol disaccharide derivative |
| *Hydroxybenzoic acids and derivatives* | | | | | | | | |
| 2 | 3.66 | 331.0716 (100) | - | - | -2.5 | 30.4 | $C_{13}H_{15}O_{10}$ | Gallic acid hexose |
| 5 | 5.39 | 315.0755(100) | - | - | -2.8 | 16.1 | $C_{13}H_{15}O_{9}$ | Dihydroxybenzoic acid hexose |
| 6 | 6.66 | 299.0810 (100) | - | 137.0217 (100) | -3.7 | 82.5 | $C_{13}H_{15}O_{8}$ | Hydroxybenzoic acid hexose |
| *Organic acids and derivatives* | | | | | | | | |
| 3 | 3.74 | 205.0374 (35) | 111.0104 (100) | - | -2.0 | 44.5 | $C_{7}H_{9}O_{7}$ | Citric acid derivative |
| 4 | 5.12 | 279.1119 (100) | - | - | -3.4 | 15.3 | $C_{11}H_{19}O_{8}$ | Hydroxyvaleric acid hexose |
| 39 | 8.85 | 366.1285 (100) | 733.2537 (24) | 204.0706 (62); 186.0619 (74); 142.0688 (100) | -5.8 | 11.0 | $C_{17}H_{20}NO_{8}$ | Indole-3-lactic acid hexose |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| *Hydroxycinnamic acids and derivatives* | | | | | | | | | |
| 7 | 6.81 | 616.1186 (100) | - | 167.0157 (81); 149.0121 (100) | -9.6 | 5.5 | $C_{23}H_{26}N_3O_{15}S$ | Glutathionyl caftaric acid |
| 9 | 6.98 | 646.1653 (100) | - | 193.0002 (100) | -10.6 | 23.5 | $C_{25}H_{32}N_3O_{15}S$ | Glutathionyl caffeic acid derivative |
| 10 | 7.12 | 616.1190 (100) | - | 167.0212 (100); 149.0085 (85) | -10.0 | 4.8 | $C_{23}H_{26}N_3O_{15}S$ | Glutathionyl caftaric acid |
| 11 | 7.25 | 646.1694 (100) | - | 193.0004 (100) | -13.4 | 23.3 | $C_{25}H_{32}N_3O_{15}S$ | Glutathionyl caffeic acid derivative |
| 14 | 7.37 | 341.0927 (100) | 161.0280 (20) | 161.0284 (49); 133.0324 (100) | -4.9 | 1.8 | $C_{15}H_{17}O_9$ | Caffeic acid hexose |
| 19 | 7.59 | 327.1144 (100) | 165.0593 (47) | - | -3.5 | 6.1 | $C_{15}H_{19}O_8$ | Hydroxyhydrocinnamic acid hexose |
| 22 | 7.72 | 624.1629 (100) | - | 192.9999 (100) | 8.7 | 20.0 | $C_{23}H_{34}N_3O_{15}S$ | Glutathionylcaffeic acid derivative |
| 24 | 7.99 | 325.0984 (100) | 163.0445 (10); 145.0325 (38) | 145.0389 (54); 117.0360 (81) | -5.3 | 5.8 | $C_{15}H_{17}O_8$ | Coumaric acid hexose |
| 28 | 8.23 | 325.0983 (100) | 163.0527 (6); 145.0322 (19) | 145.0365 (54); 117.0364 (100) | -4.5 | 1.7 | $C_{15}H_{17}O_8$ | Coumaric acid hexose |
| 29 | 8.23 | 355.1085 (100) | 193.0557 (5) | 160.0206 (100); 132.0208 (59) | -5.0 | 13.0 | $C_{16}H_{19}O_9$ | Ferulic acid hexose |
| 32 | 8.36 | 355.1089 (100) | 193.0567 (34) | 160.0200 (100); 132.0208 (35) | -5.4 | 21.8 | $C_{16}H_{19}O_9$ | Ferulic acid hexose |
| *Flavanols* | | | | | | | | | |
| 8 | 6.93 | 594.1474 (100) | - | 321.0486 (100); 183.0161 (82); 167.0322 (71); 137.0225 (70); 125.0259 (65) | -7.5 | 22.4 | $C_{25}H_{28}N_3O_{12}S$ | Glutathionyl-catechin |
| 12 | 7.28 | 594.1508 (100) | - | 321.0501 (65); 183.0170 (92); 167.0386 (100); 137.0225 (87); 125.0265 (96) | -8.0 | 6.3 | $C_{25}H_{28}N_3O_{12}S$ | Glutathionyl-catechin |
| 15 | 7.37 | 577.1403 (100) | - | - | -5.2 | 9.4 | $C_{30}H_{25}O_{12}$ | Procyanidin P2 |
| 16 | 7.42 | 594.1494 (100) | - | 321.0504 (46); 183.0165 (38); 143.0484 (100); 125.0265 (50) | -9.4 | 7.9 | $C_{25}H_{28}N_3O_{12}S$ | Glutathionyl-catechin |
| 18 | 7.54 | 577.1411 (100) | - | 407.0830 (34); 289.0807 (45); 245.0844 (46); 125.0265 (100) | -5.9 | 2.6 | $C_{30}H_{25}O_{12}$ | Procyanidin P2 |
| 21 | 7.72 | 594.1506 (100) | - | 321.0501 (46); 183.0153 (50); 143.0487 (100); 125.0265 (56) | -10.7 | 5.4 | $C_{25}H_{28}N_3O_{12}S$ | Glutathionyl-catechin |
| 26 | 8.01 | 289.0751 (18) | | - | -9.9 | 17.7 | $C_{15}H_{13}O_6$ | Catechin/Epicatechin |
| 33 | 8.44 | 865.2069 (100) | 289.0751 | - | -8.4 | 18.8 | $C_{45}H_{37}O_{18}$ | Procyanidin C1 |

| 34 | 8.50 | 289.0763 (100) | 125.0252 (11) | 123.0430 (100); 109.0301 (55) | -4.3 | 11.0 | $C_{15}H_{13}O_6$ | Catechin/Epicatechin |
|---|---|---|---|---|---|---|---|---|
| 37 | 8.67 | 865.2069 (100) | 289.0751 | - | -8.4 | 18.8 | $C_{45}H_{37}O_{18}$ | Procyanidin C1 |
| *Amino acids* | | | | | | | | |
| 13 | 7.32 | 203.0859 (100) | - | - | -3.3 | 22.4 | $C_{11}H_{11}N_2O_2$ | Tryptophan |
| *Terpenoid derivatives* | | | | | | | | |
| 17 | 7.42 | 443.1988 (100) | - | - | 4.1 | 9.3 | $C_{21}H_{31}O_{10}$ | Dihydrophaseic acid hexose |
| 30 | 8.29 | 429.2187 (100) | - | 205.1624 (81); 153.0971 (93); 113.0246 (100) | -6.9 | 15.4 | $C_{21}H_{33}O_9$ | Tetrahydroabscisic acid hexose |
| *Flavonols* | | | | | | | | |
| 23 | 7.84 | 481.1429 | - | 177.0176 (92); 151.0420 (91); 137.0275 (99); 109.0301 (51) | -6.5 | 5.4 | $C_{22}H_{25}O_{12}$ | Myricetin derivative |
| *Anthocyanins* | | | | | | | | |
| 25 | 7.99 | 461.1161 (100) | - | 283.0299 (100) | -7.2 | 13.3 | $C_{22}H_{23}O_{11}$** | Peonidin-3-O glucoside |
| 41 | 9.25 | 463.0959 (100) | - | 301.0336 (27); 271.0309 (100); 255.0347 (54) | -7.7 | 6.1 | $C_{21}H_{19}O_{12}$** | Delphinidin-3-O-glucoside |
| 43 | 9.63 | 477.1116 (100) | - | 314.0507 (45); 285.0395 (59); 271.0312 (100); 243.0365 (92); | -7.7 | 33.9 | $C_{22}H_{22}O_{12}$** | Petunidin-3-O-glucoside |
| *Flavanonols* | | | | | | | | |
| 35 | 8.53 | 449.1138 (100) | - | - | -4.0 | 14.0 | $C_{21}H_{21}O_{11}$ | Taxifolin-deoxy hexoside A/B |
| 36 | 8.60 | 479.1142 (100) | - | - | -6.8 | 27.8 | $C_{22}H_{23}O_{12}$ | Dihydroisorhamnetin hexoside |
| 42 | 9.46 | 449.1126 (100) | - | - | -3.6 | 10.2 | $C_{21}H_{21}O_{11}$ | Taxifolin-deoxy hexoside A/B |
| *Other metabolites* | | | | | | | | |
| 40 | 9.05 | 450.1992 (100) | - | 143.0468 (100); 128.0388 (49) | | | | Gluthationyl derivative |

5 *Peak label assigned according to overall temporal elution order.

6 **[M-2H]⁻.

7

8 **Table 2.** Peak assignment of selected metabolites in 'Crimson Seedless' samples using ^{1}H-NMR.

| *Metabolite* | *Group* | *Multiplicity* | *δ H (ppm)* |
|---|---|---|---|
| Acetic acid | $CH_3$ | s | 2.03 |
| Alanine | $CH_3$ | d | 1.47 |
| γ-Aminobutirric acid (GABA) | α$CH$ | dd | 3.04 |
| Arginine | β$CH_2$<br>γ$CH_2$ | m<br>m | 1.89<br>1.68 |
| Ethanol | $CH_3$ | t | 1.17 |
| Fructose | | d<br>m<br>m | 4.10<br>4.03<br>3.99 |
| α-Glucose | $C^1H$ | d | 5.22 |
| β-Glucose | $C^1H$<br>$C^2H$ | d<br>dd | 4.63<br>3.23 |
| Isoleucine | $CH_3$ | m | 0.95 |
| Lactic acid | $CH_3$ | d | 1.32 |
| Leucine | γ$CH_3$ | t | 0.96 |
| Malic acid | β$CH$<br>β'$CH$<br>α$CH$ | dd<br>dd<br>dd | 2.59*<br>2.79*<br>4.38* |
| Proline | | m<br>m | 2.00<br>2.33 |
| Tartaric acid | $CH$ | s | 4.38* |
| Valine | γ'$CH_3$<br>γ$CH_3$ | d<br>d | 0.99<br>1.04 |

9 * Values variable in function of ion strength of the samples. (s = singlet; d = doublet; t = triplet; m =
10 multiplet).

1 **Figure Captions**

2

3 **Figure 1**: Plastic net used to collect berries spontaneously dropping from pedicel before harvest.

4

5 **Figure 2**: a) PC1/PC2 scores plot and b) PC1/PC2 loadings plot obtained by HRMS data of samples
6 collected during 2010 (HRMS detection in negative ion mode).

7

8 **Figure 3**: PC1/PC2 a) score and b) loadings plot obtained by NMR data of grape samples collected
9 during 2010.

10

11 **Figure 4**: a) HRMS(-)-NMR and b) HRMS(+)-NMR covariance plot of grape samples collected
12 during 2010.

13

14

Figure(1)
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Figure(2)
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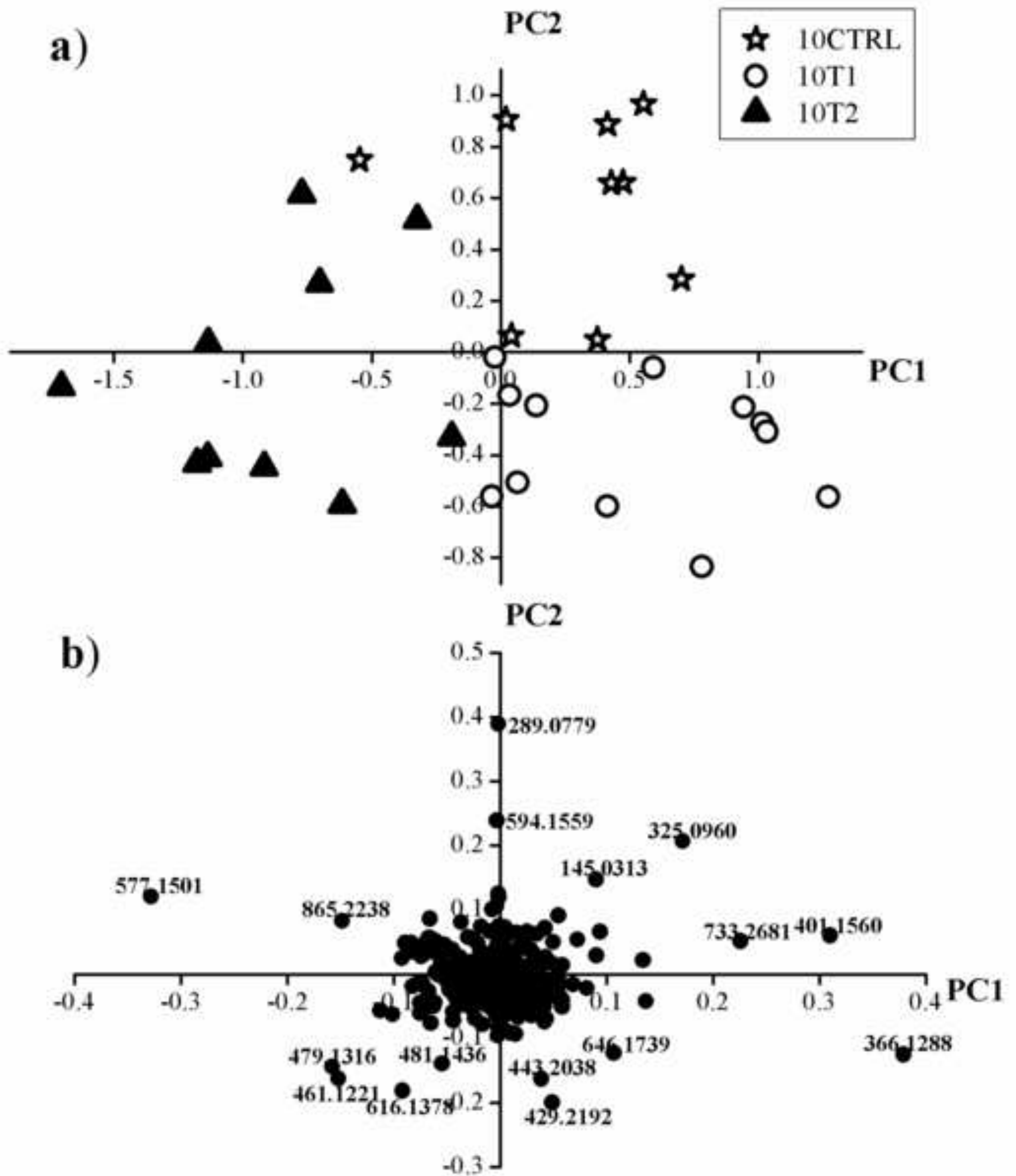

Figure(3)
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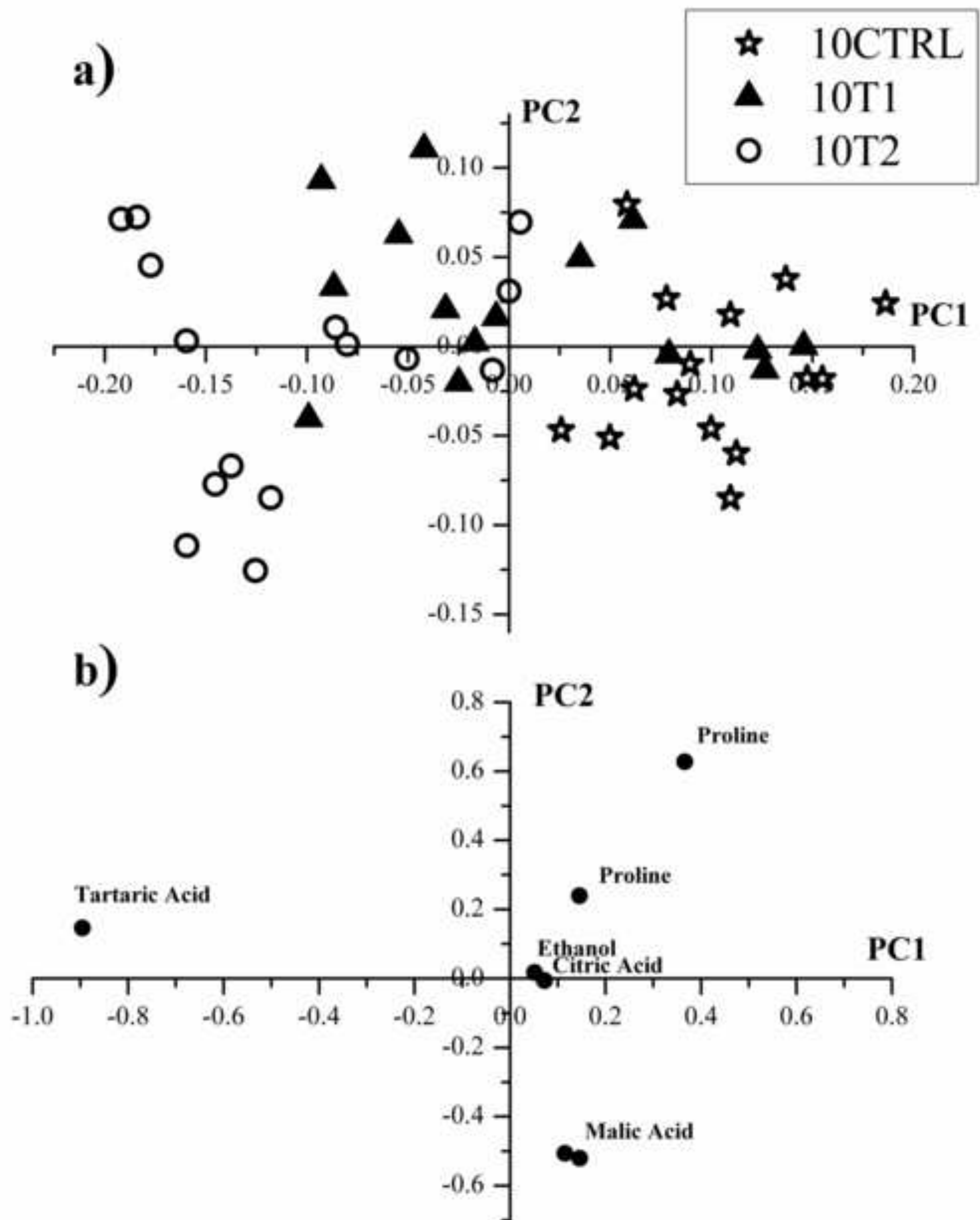

Figure(4)

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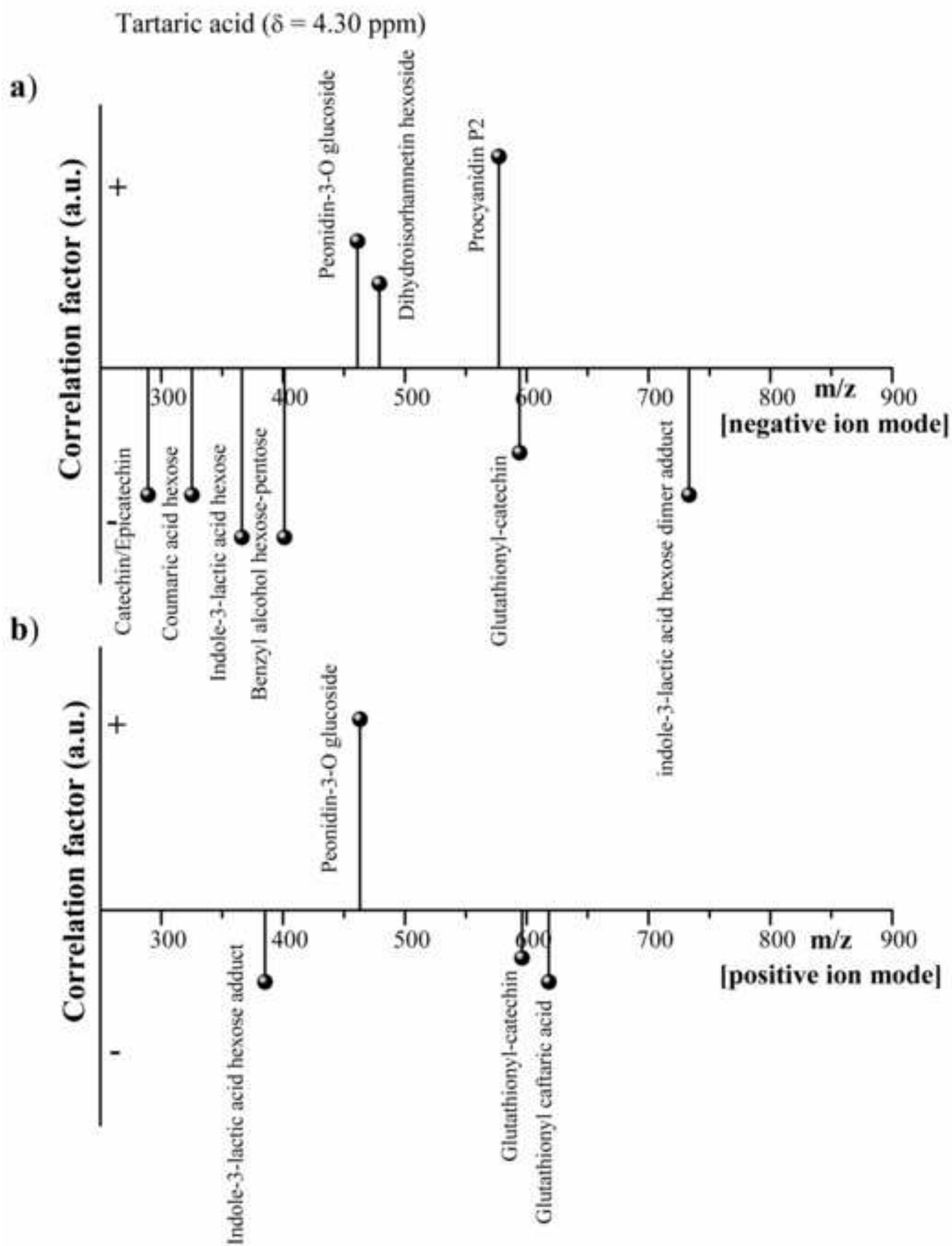

**Supplementary Material**

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