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EIMS Fragmentation and MRM quantification of ferulic and p-coumaric acid TMS derivatives in deposited atmospheric particles

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Keywords:	P-coumaric acid, ferulic acid, Mass fragmentation, MRM quantification, Atmospheric particles
Abstract:	Ferulic and p-coumaric acids are important biological and structural components of plant cell walls and possess antioxidant and antimicrobial properties. These phenolic acids are widespread in environmental samples. However, when they are present at very low concentrations or in very complex lipid extracts, their identification and quantification can be challenging. The EIMS fragmentation pathways of ferulic and p-coumaric acid TMS derivatives were investigated. These pathways were deduced by (i) low-energy CID-GC/MS/MS, (ii) accurate mass measurement, and (iii) ¹³ C labelling. These compounds were then characterized and quantified in MRM mode in total lipid extracts of deposited atmospheric particles using highly specific transitions based on the main fragmentation pathways elucidated.

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11 3 **EIMS Fragmentation and MRM quantification of**
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14 4 **ferulic and *p*-coumaric acid TMS derivatives in**
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56 30 **RATIONALE**

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8 31 Ferulic and *p*-coumaric acids are important biological and structural components of plant cell
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10 32 walls and possess antioxidant and antimicrobial properties. These phenolic acids are
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12 33 widespread in environmental samples. However, when they are present at very low
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14 34 concentrations or in very complex lipid extracts, their identification and quantification can be
15
16 35 challenging.

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19 36 **METHODS**

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21 37 The EIMS fragmentation pathways of ferulic and *p*-coumaric acid TMS derivatives were
22
23 38 investigated. These pathways were deduced by (i) low-energy CID-GC/MS/MS, (ii) accurate
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25 39 mass measurement, and (iii) ¹³C labelling. These compounds were then characterized and
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27 40 quantified in MRM mode in total lipid extracts of deposited atmospheric particles using highly
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29 41 specific transitions based on the main fragmentation pathways elucidated.

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31
32 42 **RESULTS**

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34 43 CID-MS/MS analyses, accurate mass measurement and ¹³C labelling enabled us to elucidate
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36 44 EIMS fragmentations of ferulic and *p*-coumaric acid TMS derivatives. Some specific
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38 45 fragmentations proved useful for subsequent characterization and quantification of these
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40 46 compounds. As an application of some of the described fragmentations, trace amounts of these
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42 47 phenolic acids were characterized and quantified in MRM mode in wet- and dry-deposited
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44 48 atmospheric particles containing low proportions of organic matter.

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47 49 **CONCLUSIONS**

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49 50 EIMS fragmentations of ferulic and *p*-coumaric acid TMS derivatives exhibit specific fragment
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51 51 ions that can be very useful for the quantification of trace amounts of both phenolic acids in
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53 52 environmental samples.

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3 54 **RUNNING TITLE:** Mass fragmentation of *p*-hydroxycinnamic acids
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7 56 **KEYWORDS:** EIMS fragmentation; Ferulic acid; *p*-Coumaric acid; TMS derivatives;
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10 57 Deposited atmospheric particles.
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59 1 INTRODUCTION

60 Ferulic (3-(4-hydroxy-3-methoxyphenyl)prop-2-enoic) and *p*-coumaric (3-(4-hydroxyphenyl)-
61 prop-2-enoic) acids, mostly in their *trans* isomeric forms,^[1] are common constituents of the cell
62 walls of several plant families,^[2-4] where they occur either free or bound to cell wall
63 components.^[5] The binding involves ether linkages with lignin and ester linkages with structural
64 macromolecules such as polysaccharides and proteins.^[4,6] *p*-Coumaric acid is principally
65 esterified on lignin units, and ferulic acid is both etherified to lignin and esterified to
66 hemicelluloses.^[7]

67 These secondary products of the plant metabolism have antioxidant, anti-inflammatory,
68 anti-microbial, and anti-ageing properties.^[8] They owe their highly efficient antioxidant activity
69 to their ability to scavenge free radicals, donate hydrogen atoms, electrons, or chelate metal
70 cations.^[9] Various and informative proportions of *p*-coumaric and ferulic acids are present in
71 pollen and spores, where they play a protective role against UV, microbial and physical
72 damage.^[10] These phenolic acids can thus be useful tools to trace organic matter origin in
73 atmospheric particle samples.

74 The analytical techniques commonly used to quantify phenolic acids are high
75 performance liquid chromatography (HPLC) and gas chromatography (GC), alone or in tandem
76 with mass spectrometry (MS).^[11] Despite an abundant literature,^[4,12,13] quantification of these
77 compounds in complex lipid extracts of plants or in samples containing very low amounts of
78 organic matter remains a challenge. There is thus a real need to develop methods for the
79 quantification of trace amounts of specific phenolic compounds in environmental samples.

80 Its high sensitivity and resolving power make GC/EIMS/MS a technique particularly
81 well-suited to the unambiguous detection of phenolic compounds in environmental samples.
82 Here, we set out (i) to elucidate the electron ionization (EI) fragmentation pathways of
83 trimethylsilyl (TMS) derivatives of ferulic and *p*-coumaric acids and (ii) to quantify these

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3 84 compounds in different samples of deposited atmospheric particles in multiple reaction
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5 85 monitoring (MRM) mode using highly specific transitions based on the main fragmentation
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7 86 pathways elucidated.
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11 88 **2 EXPERIMENTAL**

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16 17 90 **2.1 Chemicals**

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20 91 *N,O*-Bis(trimethylsilyl)trifluoroacetamide (BSTFA) and unlabelled *trans*-ferulic and *trans-p*-
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22 92 coumaric acids were purchased from Sigma-Aldrich (Lyon, France). *cis*-Ferulic and *cis-p*-
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24 93 coumaric acids were produced by sunlight irradiation of the *trans* isomers in methanol.^[14] Fully
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26 94 ¹³C-labelled *trans*-ferulic and *trans-p*-coumaric acids were isolated (97% ¹³C) from leaves of
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28 95 *Avena sativa* obtained from IsoLife (Wageningen, The Netherlands). This isolation involved
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30 96 alkaline hydrolysis of leaf debris and purification of the resulting total lipid extract by
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32 97 preparative thin layer chromatography (TLC) on silica gel K6 plates (Whatman, Maidstone,
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34 98 UK) after elution with CHCl₃/CH₃OH/HCOOH (85:15:1, v/v/v).
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41 100 **2.2 Sampling and treatment of deposited atmospheric particle samples**

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43 101 Wet- and dry-deposited atmospheric samples were collected at Cap Béar close to the
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45 102 Mediterranean Sea (42°30'54.82" N; 3°7'21.06" E) using an MTX ARS 1000 autosampler
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47 103 (MTX-Italia SPA, Modena, Italia) equipped with a rain sensor that automatically moves a cap
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49 104 from the dry collector to the wet collector when it rains. Prior to deployment, the buckets were
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51 105 cleaned with a 5% Decon 90 solution and rinsed with ultrapure water (Millipore, Molsheim,
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53 106 France), washed again with 5% HCl solution and finally rinsed again with ultrapure water. After
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55 107 collection, the dry deposition buckets were filled at the laboratory with 500 mL of ultrapure
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57 108 water, and the contents thoroughly leached and filtered. Wet samples were thoroughly leached
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3 109 and filtered. The samples were collected on GF/F membranes (0.7 μm , precombusted at 500°C
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5 110 for 6 h before use) and dried at 40°C for 96 h before analysis.
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8 111 Hot alkaline hydrolysis was used for free and esterified *p*-coumaric and ferulic acid
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10 112 recovery. The filters (analysed in triplicate) and 250 μL aliquots of internal standard solutions
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12 113 (2.6 and 1.4 mg/L of fully ^{13}C -labelled ferulic and *p*-coumaric acids, respectively) were placed
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14 114 in methanol (20 mL) with excess NaBH_4 (70 mg, 30 min at 20°C). This was done to reduce any
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16 115 hydroperoxides in the samples^[15] that could degrade the phenolic acids during the hot
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18 116 saponification step. Water (15 mL) and KOH (1.7 g) were then added, and the mixture was
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20 117 saponified by refluxing (2 h). After cooling, the contents of the flasks were acidified to pH 1
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22 118 with 2 N HCl and extracted three times with dichloromethane (DCM) (30 mL). The combined
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24 119 DCM extracts were then concentrated by rotary evaporation at 40°C to give the total lipid
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26 120 extract (TLE).
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33 122 2.3 Derivatisation

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35 123 The TLEs were silylated by dissolving them in 100 μL BSTFA and heating at 50°C for 1 h. The
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37 124 mixture was then diluted with ethyl acetate and analysed by mass spectrometric methods.
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39 125 Owing to the high volatility of TMS derivatives of ferulic and *p*-coumaric acids, it is most
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41 126 important to avoid the use of silylation methods that need an evaporation step (as in the case of
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43 127 classical pyridine/BSTFA mixtures).
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49 129 2.4 Gas chromatography/electron ionization quadrupole time-of-flight mass 50 51 52 130 spectrometry

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54 131 Accurate mass measurements were made in full scan mode using an Agilent 7890B/7200
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56 132 GC/QTOF system (Agilent Technologies, Parc Technopolis – ZA Courtaboeuf, Les Ulis,
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58 133 France). A cross-linked 5% phenyl-methylpolysiloxane capillary column (Agilent
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3 134 Technologies; HP-5MS Ultra inert, 30 m × 0.25 mm, film thickness 0.25 μm) was used.
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5 135 Analyses were performed with an injector operating in pulsed splitless mode set at 270°C. Oven
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7 136 temperature was ramped from 70°C to 130°C at 20°C min⁻¹ and then to 300°C at 5°C min⁻¹.
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9
10 137 The pressure of the carrier gas (He) was maintained at 0.69 × 10⁵ Pa until the end of the
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12 138 temperature program. Instrument temperatures were 300°C for the transfer line and 230°C for
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14 139 the ion source. The collision gas was nitrogen (1.5 mL min⁻¹). Accurate mass spectra were
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16 140 recorded in the range *m/z* 50–700 at 4 GHz with the collision gas opened. The QTOF-MS
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18 141 instrument provided a typical resolution ranging from 8009 to 12252 from *m/z* 68.9955 to
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20 142 501.9706. Perfluorotributylamine (PFTBA) was used for daily MS calibration.
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26 144 2.5 Gas chromatography/electron ionization tandem mass spectrometry

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29 145 GC/EIMS and GC/EIMS/MS experiments were conducted using a model 7890A/7010 tandem
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31 146 quadrupole gas chromatography system (Agilent Technologies, Parc Technopolis – ZA
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33 147 Courtaboeuf, Les Ulis, France). A cross-linked 5% phenyl-methylpolysiloxane HP-5MS Ultra
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35 148 inert capillary column (Agilent Technologies; 30 m × 0.25 mm, film thickness 0.25 μm) was
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37 149 used. Analyses were performed with an injector operating in pulsed splitless mode set at 270°C.
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40 150 The oven temperature was ramped from 70°C to 130°C at 20°C min⁻¹, then to 250°C at 5°C
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42 151 min⁻¹ and finally to 300°C at 3°C min⁻¹. The pressure of the carrier gas (He) was held at 0.69
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44 152 × 10⁵ Pa until the end of the temperature program and then ramped from 0.69 × 10⁵ Pa to 1.49
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46 153 × 10⁵ Pa at 0.04 × 10⁵ Pa min⁻¹. The mass spectrometry conditions were: electron energy,
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48 154 70 eV; transfer line temperature, 300°C; source temperature, 230°C; quadrupole 1 temperature,
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50 155 150°C; quadrupole 2 temperature, 150°C; collision gas (N₂) flow rate, 1.5 mL min⁻¹ quench
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52 156 gas (He) flow rate, 2.25 mL min⁻¹; mass range, *m/z* 50–700; cycle time, 313 ms.
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55 157 Collision-induced dissociation (CID) was optimised by using collision energies of 5, 10, 15 and
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3 RESULTS AND DISCUSSION

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3.1 EIMS fragmentation of *p*-coumaric acid TMS derivative

The TOF mass spectrum of the TMS derivative of *p*-coumaric acid (Figure 1A) displayed a molecular peak at m/z 308.1266 (ions $\mathbf{a}^{+\bullet}$, $\mathbf{b}^{+\bullet}$ or $\mathbf{f}^{+\bullet}$) and intense peaks at m/z 293.1027, 249.1130 and 219.0835 corresponding to losses of CH_3 , $\text{C}_2\text{H}_3\text{O}_2$ and $\text{C}_3\text{H}_9\text{OSi}$, respectively.

The fragmentation pathways in Figure 2 are proposed to explain the formation of these ions.

Ionization of the ester group of the *p*-coumaric acid TMS derivative can take place on the double-bonded oxygen or on the oxygen linked to the TMS group, giving ions $\mathbf{a}^{+\bullet}$ and $\mathbf{b}^{+\bullet}$,

respectively (Figure 2). Ion $\mathbf{a}^{+\bullet}$ can easily lose TMSO^\bullet to give the ion \mathbf{c}^+ at m/z 219.0835 strongly stabilized by conjugation.^[16] However, CID analyses (Table 1) showed that this ion

could also be produced from ion \mathbf{d}^+ at m/z 293.1027 resulting from the loss of a methyl radical by the molecular ion $\mathbf{b}^{+\bullet}$. This fragmentation should entail the loss of a neutral $(\text{CH}_3)_2\text{Si}=\text{O}$ by

the fragment ion \mathbf{d}^+ as depicted in Figure 2. This ion can also lose a neutral molecule of CO_2 as previously proposed by Brook et al.^[17] in the case of triphenylsilyl benzoates to give the ion \mathbf{e}^+

at m/z 249.1130 also strongly stabilized by conjugation (Figure 2). The shifts of molecular ions ($\mathbf{a}^{+\bullet}$, $\mathbf{b}^{+\bullet}$ or $\mathbf{f}^{+\bullet}$) and fragment ions \mathbf{c}^+ , \mathbf{d}^+ and \mathbf{e}^+ to m/z 317.1551 $[\text{M}]^{+\bullet}$, 228.1142 $[\text{M} - \text{TMSO}]^+$,

302.1325 $[\text{M} - \text{CH}_3]^+$ and 257.1391 $[\text{M} - \text{CH}_3 - {}^{13}\text{CO}_2]^+$, respectively, in TOF MS of fully ^{13}C -labelled *p*-coumaric acid TMS derivative (Figure 1B) strongly support the proposed

fragmentation pathways. The low deviations (ranging from +2.5 to -0.8 ppm) observed between accurate and calculated masses of ions $\mathbf{a-e}$ (charges not shown) confirm the elemental

composition of the proposed fragment ions (Table 2).

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3.2 EIMS fragmentation of ferulic acid TMS derivative

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3 184 The TOF mass spectrum of the ferulic acid TMS derivative displayed a molecular peak at m/z
4 338.1371 and intense peaks at m/z 323.1133, 308.0902, 293.0661, 279.1240, 249.0934 and
5 185 219.0478 (Figure 1C). Fragment ions at m/z 249.0934, 323.1133 and 279.1240 correspond to
6 186 ions \mathbf{c}^+ , \mathbf{d}^+ and \mathbf{e}^+ , respectively, whose formation is described above (Figure 2). It was
7 187 previously demonstrated that compounds possessing a methoxy and a TMS group in the 1,2
8 188 positions on an aromatic ring can undergo consecutive losses of two methyl radicals to give a
9 189 stable cyclic radical cation.^[18] In the case of the molecular ion \mathbf{f}^{\bullet} of the ferulic acid TMS
10 190 derivative, this process gives the ion \mathbf{h}^{\bullet} at m/z 308.0902 (Figure 2), which can then lose another
11 191 methyl radical to give the stable cation \mathbf{i}^+ at m/z 293.0661.^[19] Interestingly, ion \mathbf{j}^{\bullet} resulting
12 192 from the transfer of the charge of ion \mathbf{h}^{\bullet} to the ester group can undergo cleavages similar to
13 193 the molecular ion (i.e. direct loss of TMSO^{\bullet} or loss of methyl radical followed by neutral
14 194 $(\text{CH}_3)_2\text{Si}=\text{O}$ and CO_2 elimination) to give ions \mathbf{l}^+ and \mathbf{m}^+ at m/z 219.0478 and 249.0762,
15 195 respectively, (Figure 2). Although the masses of ions \mathbf{c}^+ and \mathbf{m}^+ were too close to be discerned
16 196 in GC-QTOF analyses, ^{13}C labelling gave strong support to the proposed fragmentation
17 197 pathways. The shifts of molecular ions (\mathbf{a}^{\bullet} , \mathbf{b}^{\bullet} or \mathbf{f}^{\bullet}) and fragment ions \mathbf{d}^+ or \mathbf{g}^+ , \mathbf{h}^{\bullet} or \mathbf{j}^{\bullet} , \mathbf{i}^+
18 198 or \mathbf{k}^+ , \mathbf{e}^+ , \mathbf{c}^+ , \mathbf{m}^+ and \mathbf{l}^+ to m/z 348.1697 $[\text{M}]^{\bullet}$, 333.1464 $[\text{M} - \text{CH}_3]^+$, 317.1198 $[\text{M} - \text{CH}_3 -$
19 199 $^{13}\text{CH}_3]^{\bullet}$, 302.0980 $[\text{M} - 2\text{CH}_3 - ^{13}\text{CH}_3]^+$, 288.1528 $[\text{M} - \text{CH}_3 - ^{13}\text{CO}_2]^+$, 259.1283 $[\text{M} -$
20 200 $\text{TMSO}]^+$, 257.1030 $[\text{M} - 2\text{CH}_3 - ^{13}\text{CH}_3 - ^{13}\text{CO}_2]^+$ and 228.0771 $[\text{M} - \text{CH}_3 - ^{13}\text{CH}_3 - \text{TMSO}]^+$,
21 201 respectively, in TOF MS of fully ^{13}C -labelled ferulic acid TMS derivative (Figure 1D) are in
22 202 close agreement with these fragmentations. Moreover, CID analyses of ^{13}C -labelled and
23 203 unlabelled ferulic acid TMS derivative confirmed the production of ions \mathbf{l}^+ and \mathbf{m}^+ from ion \mathbf{j}^{\bullet}
24 204 and that of ions \mathbf{h}^{\bullet} and \mathbf{i}^+ from ion \mathbf{g}^+ (Table 1). The small differences (ranging from +2.9 to
25 205 -1.8 ppm) observed between measured and calculated accurate masses of these different ions
26 206 (Table 3) also validate the proposed fragmentation mechanisms.
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3 208 The driving force for the formation of ions \mathbf{c}^+ , \mathbf{e}^+ , \mathbf{l}^+ and \mathbf{m}^+ is their strong stabilization by
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5 209 conjugation with the double bond and the aromatic ring. These fragmentations are thus not
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8 210 specific to TMS derivatives of cinnamic acids but can also be observed in EI mass spectra of
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10 211 TMS derivatives of all benzoic acids (e.g. *p*-hydroxybenzoic and vanillic acids) (Figures 3A
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12 212 and 3B), where the benzylic charge is also highly conjugated with the aromatic ring. By
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14 213 contrast, they are totally lacking in EI mass spectra of TMS derivatives of aromatic acids where
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16 214 this conjugation is not possible, as is the case for the 3-(4-hydroxyphenyl)propanoic acid
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18 215 (phloretic acid) TMS derivative (Figure 3B).
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23 24 217 3.3 MRM quantification of ferulic and *p*-coumaric acid TMS derivatives in 25 26 218 environmental samples 27

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29 219 As an application, the fragmentation pathways described in the previous section were used
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31 220 together with retention times to identify and quantify TMS derivatives of ferulic and *p*-coumaric
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33 221 acids in TLEs of wet- and dry-deposited atmospheric particles collected in the south of France.
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35 222 Silylated TLEs were analyzed in MRM mode using the following specific transitions selected
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37 223 on the basis of the fragmentation pathways described above (Figure 2): m/z 293 \rightarrow 219 ($\mathbf{d}^+ \rightarrow$
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39 224 \mathbf{c}^+) and m/z 323 \rightarrow 279 ($\mathbf{d}^+ \rightarrow \mathbf{e}^+$) for unlabelled *p*-coumaric and ferulic acids, respectively, and
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41 225 m/z 302 \rightarrow 228 ($\mathbf{d}^+ \rightarrow \mathbf{c}^+$) and m/z 333 \rightarrow 288 ($\mathbf{d}^+ \rightarrow \mathbf{e}^+$) for the fully ^{13}C -labelled corresponding
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43 226 internal standards.
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47 227 The limits of detection (10 pg and 30 pg for the TMS derivatives of *p*-coumaric and ferulic
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49 228 acids, respectively) were determined for a signal-to-noise ratio greater than 5. Linear responses
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51 229 with coefficients of determination $R^2 > 0.99$ could be obtained in the ranges 0.01–1 ng and
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53 230 0.03–3 ng for the TMS derivatives of *p*-coumaric and ferulic acids, respectively.
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57 231 Comparison of mass spectral data and retention times with those of standards allowed
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59 232 unambiguous characterization of TMS derivatives of *trans-p*-coumaric and *trans*-ferulic acids
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3 233 in all the samples analysed (see example in Figure 4). Large proportions of the *cis* isomers of
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5 234 these compounds could also be detected (Figure 4). The similar isomerization observed in the
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7 235 case of ¹³C-labelled internal standards (Figure 5) clearly demonstrates that these *cis* isomers
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9 236 were not present in the samples investigated but were produced during the treatment. This
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11 237 finding is very surprising since alkaline hydrolysis is often used to recover esterified phenolic
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13 238 acid.^[12] Photoisomerization of hydroxycinnamic acids is well-known^[20] and it was previously
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15 239 demonstrated that *trans-p*-coumaric and *trans*-ferulic acids underwent *cis* isomerization in
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17 240 methanol during light exposure at ambient temperature.^[21] However, in the present work,
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19 241 alkaline hydrolyses were carried out in a foil-covered vessel and TLEs were stored in amber
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21 242 vials. Moreover, we note that a marked increase in the proportion of *cis* isomers (up to 80%)
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23 243 could be observed when the alkaline hydrolysis mixture was stored at 4°C for 24 h in the dark.
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25 244 As previously suggested by Istasse et al.^[22], light is clearly not the main cause of the
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27 245 isomerisation, which seems instead to be caused by the alkaline conditions used.

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33 246 *Cis* and *trans* isomers were summed during the quantification of *p*-coumaric and ferulic
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35 247 acids in the different samples analysed. The results obtained (Table 4), show a high variability,
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37 248 with ferulic acid content ranging from 13.2 ± 4 to 199.7 ± 29.7 $\mu\text{g g}^{-1}$ and *p*-coumaric acid
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39 249 content from 28.4 ± 3.5 to 895.1 ± 2.9 $\mu\text{g g}^{-1}$ in October 2019 and April 2020, respectively.
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41 250 These large differences in values are probably due to the presence of angiosperm/gymnosperm
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43 251 pollens enriched in phenolic compounds during springtime. Pollen grains are released from
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45 252 terrestrial vegetation in large quantities, with different vegetation types delivering pulses into
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47 253 the atmosphere at varying times of the year.^[23] In the sampling region, production of pollens
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49 254 (dominated by pine, oak, cypress, plane, plantain and grasses)^[24] runs generally from February
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51 255 to the end of July.^[25] The presence of pine and oak pollens relatively enriched in *p*-coumaric
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53 256 esters^[26,27] could explain the very high *p*-coumaric acid/ferulic acid ratios observed in some
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55 257 spring samples (Table 4).
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6 259 **4 CONCLUSIONS**

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8 260 EIMS fragmentations of *p*-coumaric and ferulic acids were elucidated using low-energy
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10 261 CID-MS/MS, ¹³C labelling and accurate mass measurements. Specific MRM transitions based
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12 262 on the fragmentation pathways elucidated were selected and applied to different wet- and dry-
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14 263 deposited atmospheric particle samples collected in the south of France. These transitions
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16 264 proved very useful for identifying and quantifying relatively small amounts of these phenolic
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18 265 acids in complex lipid extracts. We note that a strong *cis*-isomerization of *p*-coumaric and
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20 266 ferulic acid was observed during alkaline hydrolysis of the samples. In any further work to
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22 267 determine the processes responsible for this isomerization, great care should thus be taken when
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24 268 quantifying *cis*- and *trans*-hydroxycinnamic acids in environmental samples involving alkaline
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FIGURE CAPTIONS

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353 **Figure 1.** TOF mass spectra of TMS derivatives of unlabelled *p*-coumaric (A), fully ¹³C-
354 labelled *p*-coumaric (B), unlabelled ferulic (C), and fully ¹³C-labelled ferulic (D) acids.

355

356 **Figure 2.** Proposed fragmentation pathways of TMS derivatives of *p*-coumaric and ferulic
357 acids.

358

359 **Figure 3.** TOF mass spectra of TMS derivatives of *p*-hydroxybenzoic (A), vanillic (B), and
360 phloretic (C) acids.

361

362 **Figure 4.** MRM chromatograms (*m/z* 323 → 279) (A) and (*m/z* 293 → 219) (B) showing the
363 presence of *cis*- and *trans*-ferulic and *p*-coumaric acid TMS derivatives, respectively, in the
364 silylated TLE of wet atmospheric deposits collected on 30 April 2020.

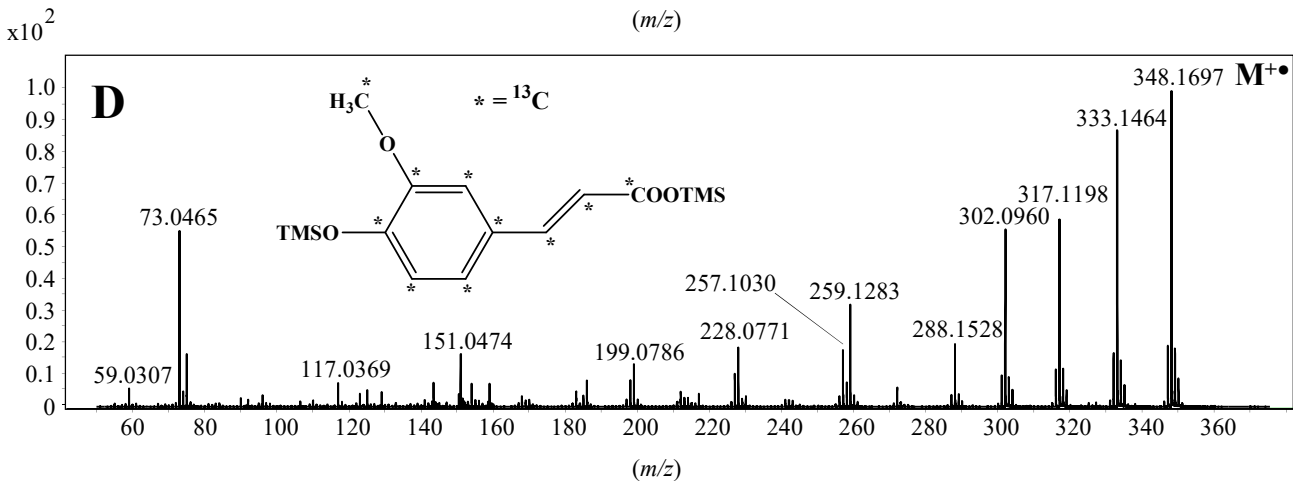
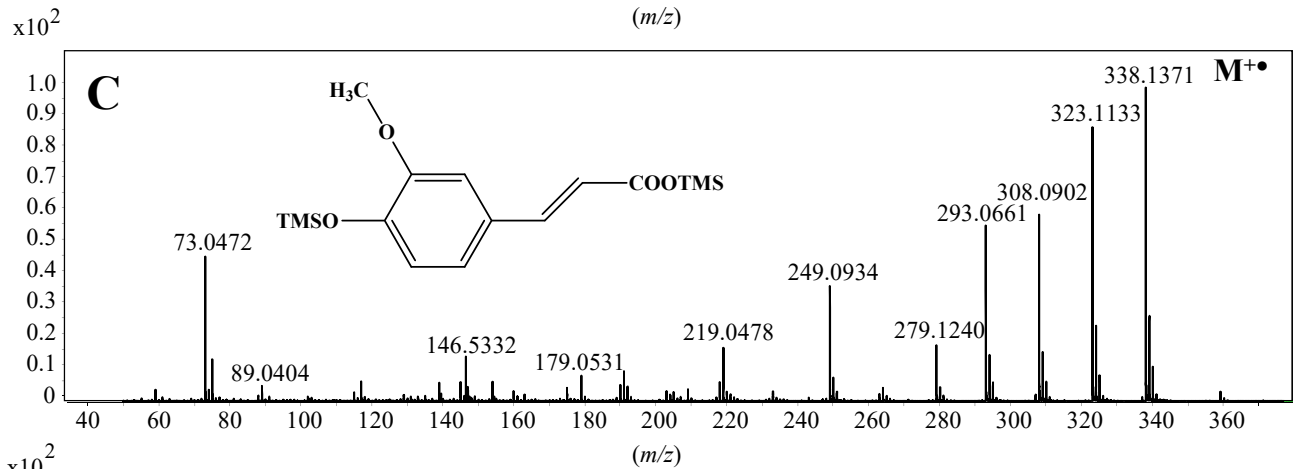
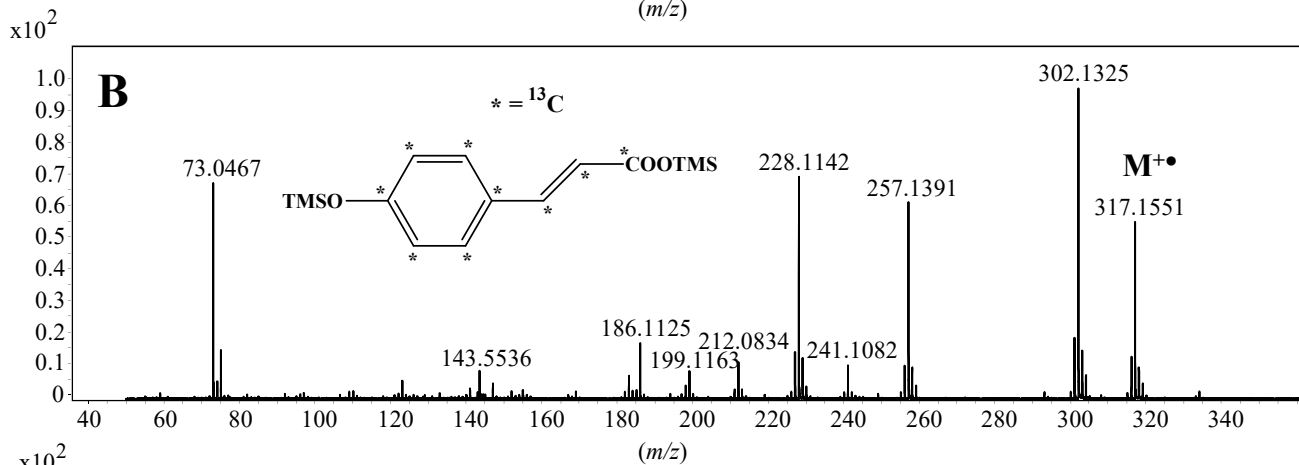
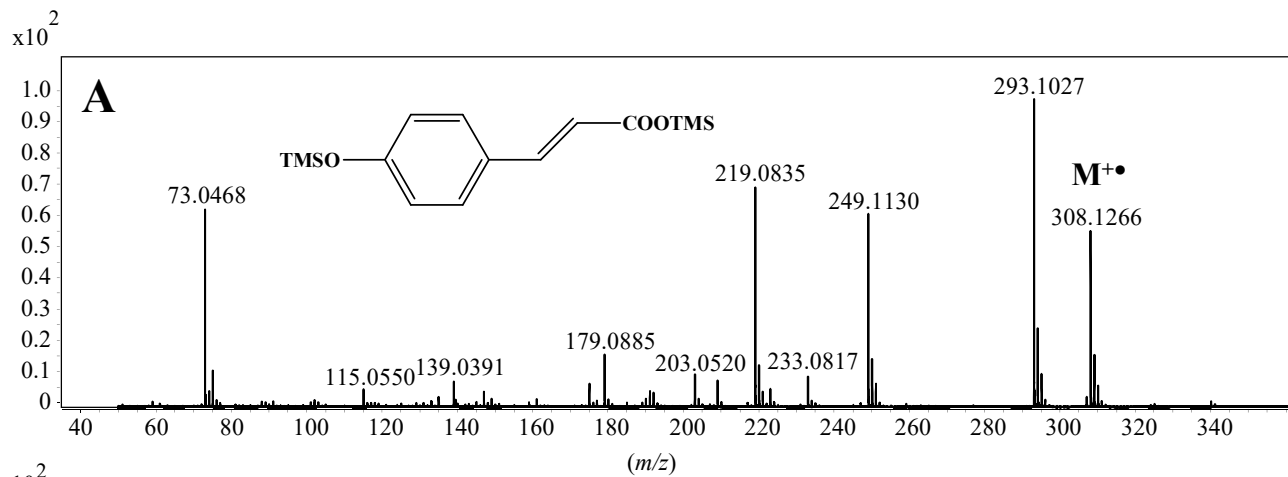
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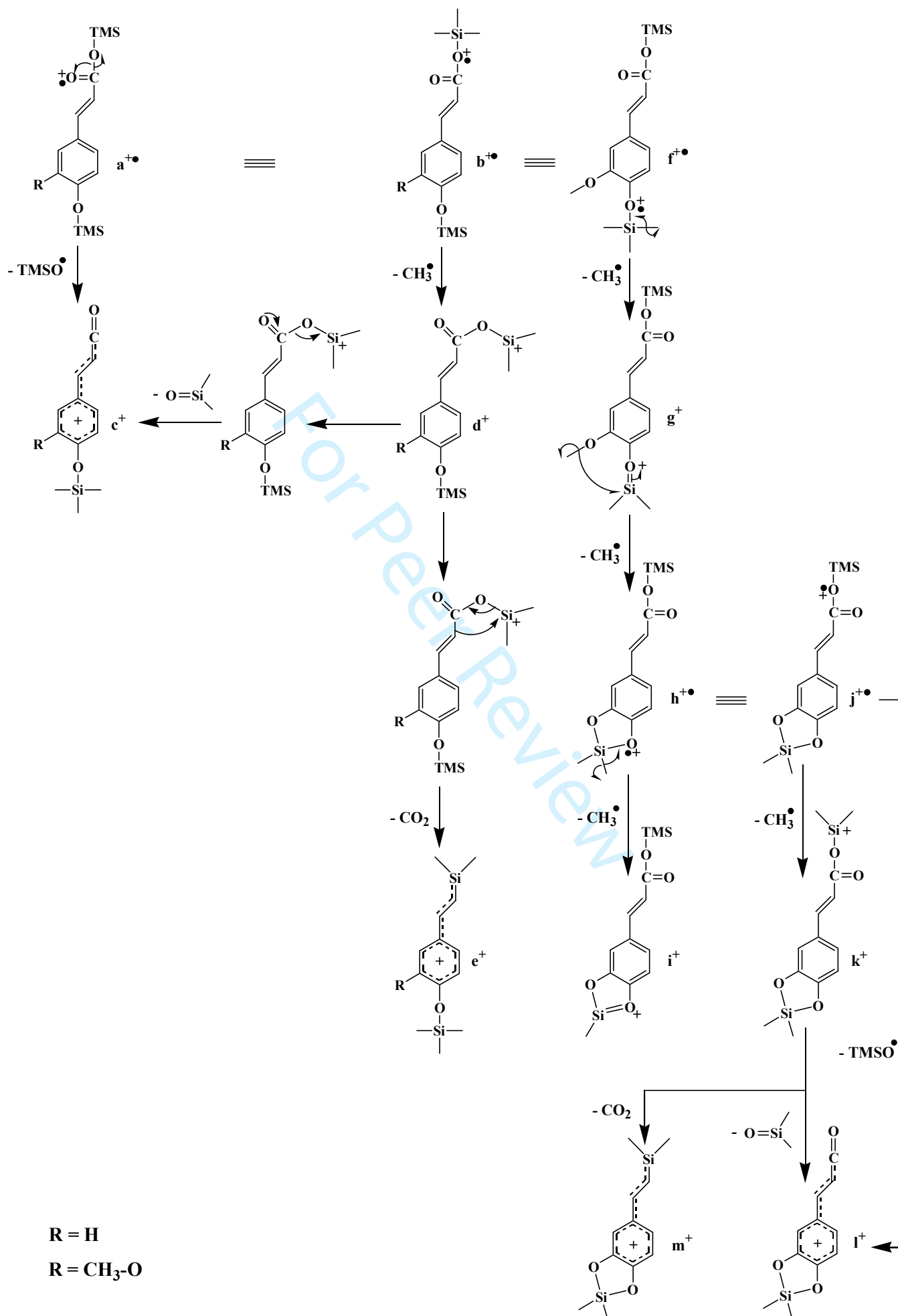
366 **Figure 5.** MRM chromatograms (*m/z* 333 → 288) of fully ¹³C-labelled ferulic acid TMS
367 derivative before the treatment (A) and after (B).

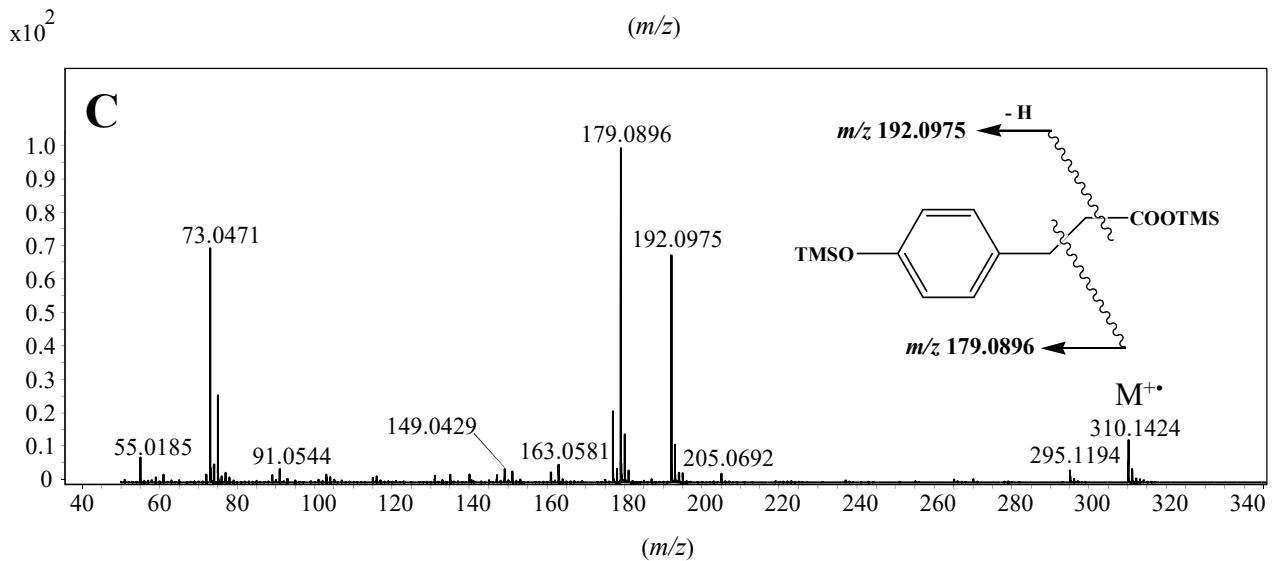
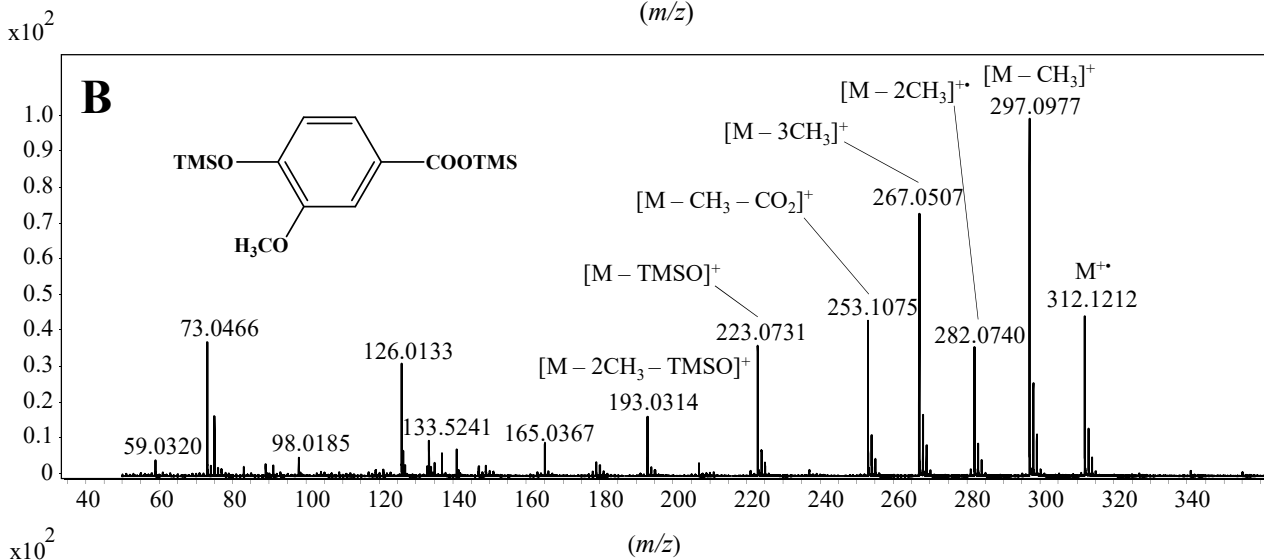
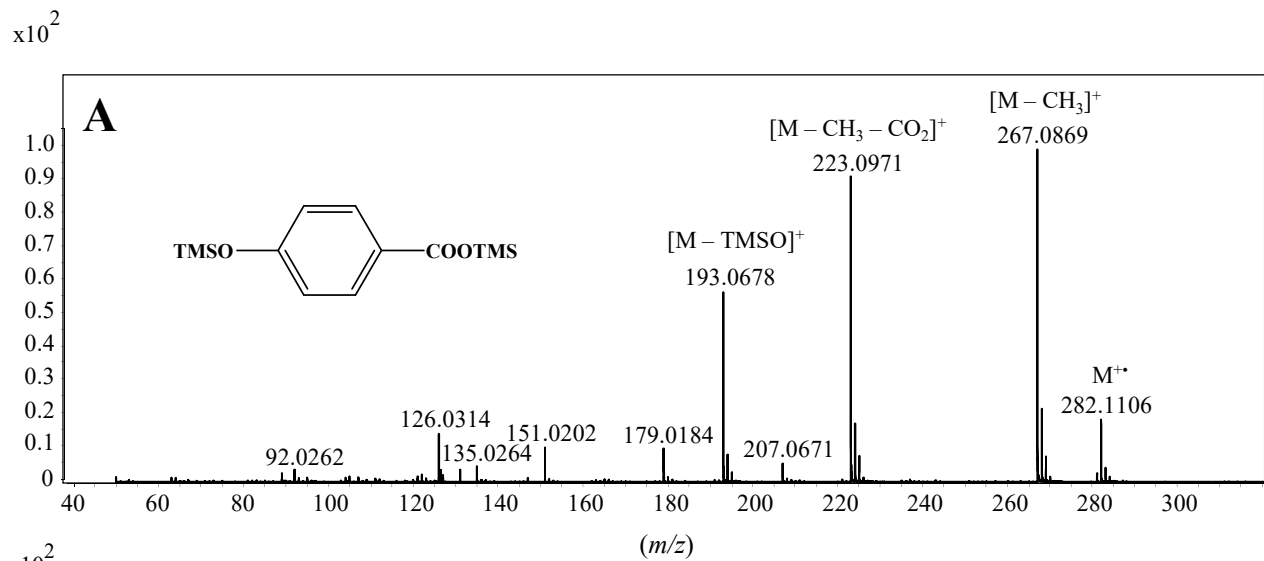
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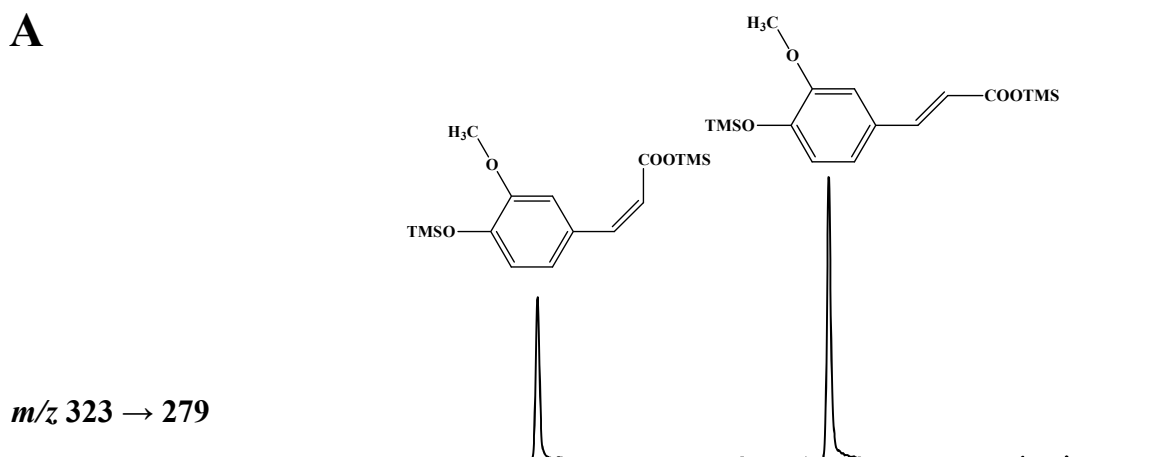
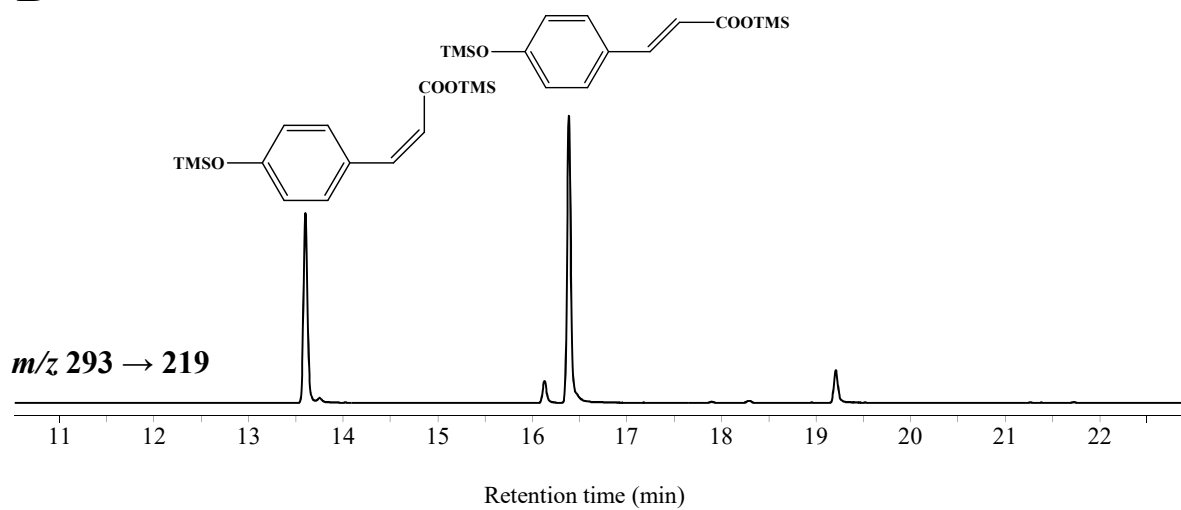
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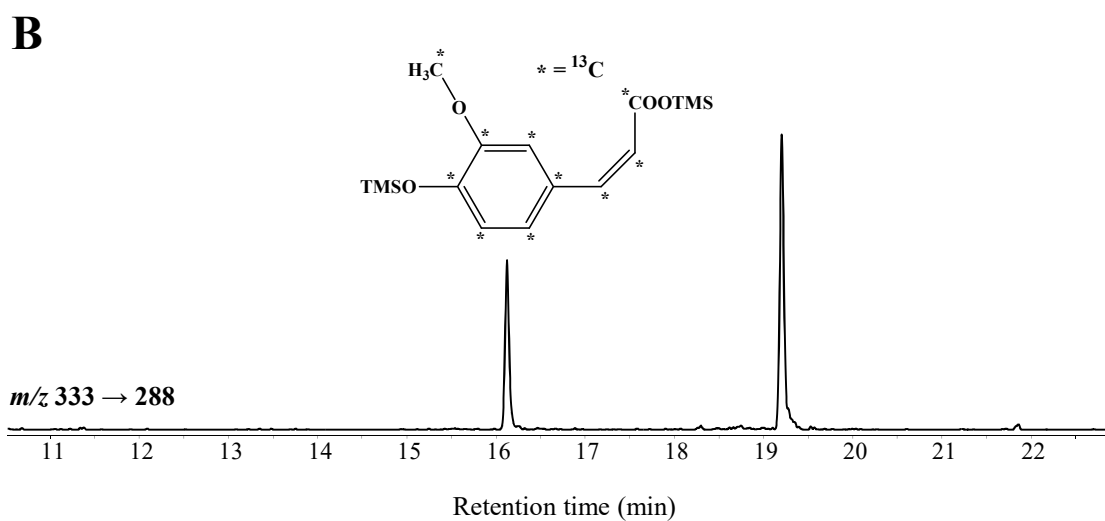
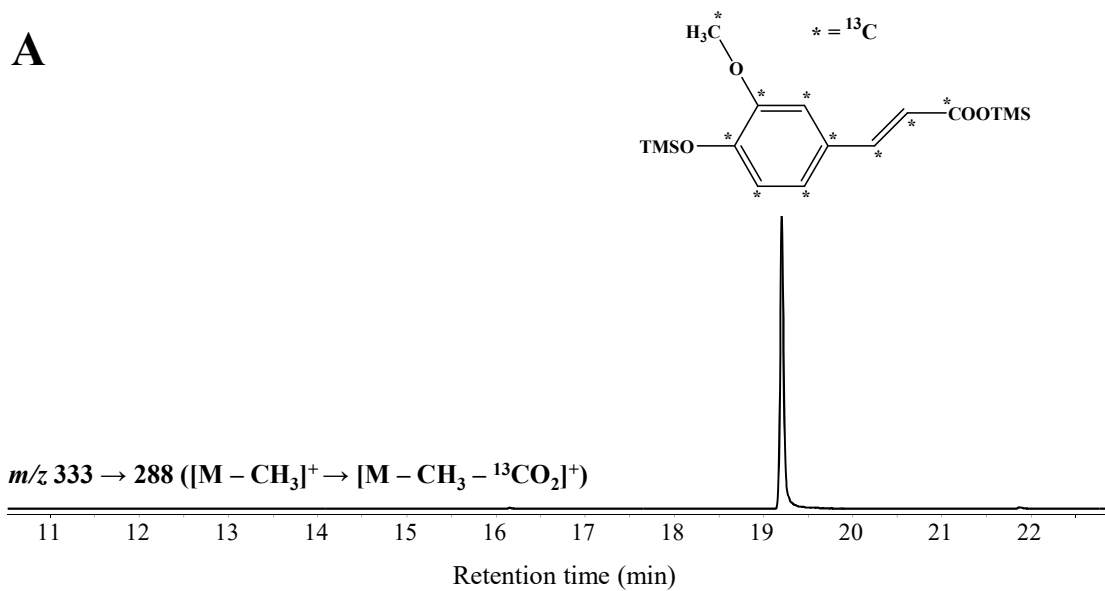


TABLE 1 CID analyses of fragment ions.

Code	<i>m/z</i>	Collision energy (eV)	Product ions
d⁺	293 ^a	10	293(49), 249 [- CO ₂] (79), 233(13), 223(9), 219 [- (CH ₃) ₂ Si=O] (100), 203(6), 73(10)
d⁺	302 ^b	10	302(51), 257 [- ¹³ CO ₂] (84), 241(13), 229(10), 228 [- (CH ₃) ₂ Si=O] (100), 212(6), 147(5), 73(12)
d⁺, g⁺	323 ^c	10	323(61), 308 [- CH ₃] (72), 293 [-2 CH ₃] (42), 279 [- CO ₂] (52), 264(9), 249 [- (CH ₃) ₂ Si=O] (100), 179(8), 175(4), 73(3)
d⁺, g⁺	333 ^d	10	333(58), 317 [- ¹³ CH ₃] (68), 302 [- ¹³ CH ₃ - CH ₃] (48), 288 [- ¹³ CO ₂] (55), 272(15), 259 [- (CH ₃) ₂ Si=O] (100), 257(16), 186(9), 183(5), 154(3), 73(5)
h^{+•}, j^{+•}	308 ^c	20	308(3), 293 [- CH ₃] (75), 265(3), 249 [- CH ₃ - CO ₂] (97), 233(9), 219 [- CH ₃ - (CH ₃) ₂ Si=O] (100), 192(6), 179(31), 73(3)
h^{+•}, j^{+•}	317 ^d	10	317(3), 302 [- CH ₃] (75), 257 [- CH ₃ - ¹³ CO ₂] (98), 241(9), 228 [- CH ₃ - (CH ₃) ₂ Si=O] (100), 199(9), 198(5), 186(32), 73(2)

^a TMS derivative of unlabelled *p*-coumaric acid

^b TMS derivative of fully ¹³C-labelled *p*-coumaric acid

^c TMS derivative of unlabelled ferulic acid

^d TMS derivative of fully ¹³C-labelled ferulic acid

TABLE 2 High-accuracy mass spectral data for ions of unlabelled and fully ^{13}C labelled *p*-coumaric acid TMS derivatives.

Code	Formula	<i>m/z</i> observed	<i>m/z</i> calculated	Δ (ppm)
a^{+•}, b^{+•}	$^{12}\text{C}_{15}\text{H}_{24}\text{O}_3\text{Si}_2^{+\bullet}$	308.1266	308.1258	+2.6
a^{+•}, b^{+•}	$^{13}\text{C}_9^{12}\text{C}_6\text{H}_{24}\text{O}_3\text{Si}_2^{+\bullet}$	317.1551	317.1550	-0.3
c⁺	$^{12}\text{C}_{12}\text{H}_{15}\text{O}_2\text{Si}^+$	219.0835	219.0836	-0.5
c⁺	$^{13}\text{C}_9^{12}\text{C}_3\text{H}_{15}\text{O}_2\text{Si}^+$	228.1142	228.1138	-1.0
d⁺	$^{12}\text{C}_{14}\text{H}_{21}\text{O}_3\text{Si}_2^+$	293.1027	293.1024	+1.0
d⁺	$^{13}\text{C}_9^{12}\text{C}_5\text{H}_{21}\text{O}_3\text{Si}_2^+$	302.1325	302.1326	-0.3
e⁺	$^{12}\text{C}_{13}\text{H}_{21}\text{OSi}_2^+$	249.1130	249.1125	+2.0
e⁺	$^{13}\text{C}_8^{12}\text{C}_5\text{H}_{21}\text{OSi}_2^+$	257.1391	257.1393	-0.8

TABLE 3 High-accuracy mass spectral data for ions of unlabelled and fully ^{13}C labelled ferulic acid TMS derivatives.

Code	Formula	m/z observed	m/z calculated	Δ (ppm)
a^{+•}, b^{+•}, f^{+•}	$^{12}\text{C}_{16}\text{H}_{26}\text{O}_4\text{Si}_2^{+\bullet}$	338.1371	338.1368	+1.8
a^{+•}, b^{+•}, f^{+•}	$^{13}\text{C}_{10}\text{C}_6\text{H}_{26}\text{O}_4\text{Si}_2^{+\bullet}$	348.1697	348.1700	-0.9
c⁺	$^{12}\text{C}_{13}\text{H}_{17}\text{O}_3\text{Si}^+$	249.0934	249.0941	+2.8
c⁺	$^{13}\text{C}_{10}\text{C}_3\text{H}_{17}\text{O}_3\text{Si}^+$	259.1283	259.1278	+1.9
d⁺, g⁺	$^{12}\text{C}_{15}\text{H}_{23}\text{O}_4\text{Si}_2^+$	323.1133	323.1130	+0.9
d⁺, g⁺	$^{13}\text{C}_{10}\text{C}_5\text{H}_{23}\text{O}_4\text{Si}_2^+$	333.1464	333.1466	-1.0
e⁺	$^{12}\text{C}_{14}\text{H}_{23}\text{O}_2\text{Si}_2^+$	279.1240	279.1232	+2.9
e⁺	$^{13}\text{C}_9\text{C}_5\text{H}_{23}\text{O}_2\text{Si}_2^+$	288.1528	288.1533	-1.7
h^{+•}, j^{+•}	$^{12}\text{C}_{14}\text{H}_{20}\text{O}_4\text{Si}_2^{+\bullet}$	308.0902	308.0895	+2.3
h^{+•}, j^{+•}	$^{13}\text{C}_9\text{C}_5\text{H}_{20}\text{O}_4\text{Si}_2^{+\bullet}$	317.1198	317.1200	-0.6
i⁺, k⁺	$^{12}\text{C}_{13}\text{H}_{17}\text{O}_4\text{Si}_2^+$	293.0661	293.0660	+0.3
i⁺, k⁺	$^{13}\text{C}_9\text{C}_4\text{H}_{17}\text{O}_4\text{Si}_2^+$	302.0960	302.0962	-0.7
l⁺	$^{12}\text{C}_{11}\text{H}_{11}\text{O}_3\text{Si}^+$	219.0478	219.0472	+2.7
l⁺	$^{13}\text{C}_9\text{C}_2\text{H}_{11}\text{O}_3\text{Si}^+$	228.0771	228.0769	+0.9
m⁺	$^{13}\text{C}_8\text{C}_4\text{H}_{17}\text{O}_2\text{Si}_2^+$	257.1030	257.1031	-0.4

TABLE 4 Concentrations and daily mass fluxes of *p*-coumaric and ferulic acids in atmospheric deposits collected in the south of France.

Sampling date (Start-End)	Type of atmospheric deposits	Daily mass fluxes (mg m ⁻² d ⁻¹)	<i>p</i> -coumaric acid (μg g ⁻¹)	Ferulic acid (μg g ⁻¹)	Daily <i>p</i> -coumaric acid fluxes (μg m ⁻² d ⁻¹)	Daily ferulic acid fluxes (μg m ⁻² d ⁻¹)	<i>p</i> -Coumaric acid /ferulic acid
21/02/-07/03/2013	Dry	36.37	502.7 ± 2.5	176.4 ± 9.7	18.3 ± 0.1	6.4 ± 0.4	2.86
14/10-31/10/2016	Dry	37.98	78.5 ± 8.6	45.0 ± 15.1	2.9 ± 0.3	1.7 ± 0.6	1.71
24/01-02/02/2017	Wet	28.36	566.7 ± 15.0	149.6 ± 54.3	16.1 ± 0.4	4.2 ± 1.6	3.83
03/02-16/02/2017	Wet	47.36	302.0 ± 54.1	157.4 ± 2.9	14.3 ± 2.6	7.5 ± 1.4	1.91
10/10-24/10/2019	Wet	476.23	28.4 ± 3.5	13.2 ± 4.0	13.5 ± 1.7	6.3 ± 1.9	2.14
12/04-30/04/2020	Wet	65.17	895.1 ± 2.9	199.7 ± 29.7	58.3 ± 0.2	13.0 ± 1.9	4.48
16/01-24/01/2020	Wet	215.13	98.6 ± 17.5	42.6 ± 7.4	21.2 ± 3.8	9.2 ± 1.6	2.30
19/02-24/02/2021	Wet	826.80	80.5 ± 3.6	36.4 ± 6.5	66.6 ± 2.9	30.0 ± 5.4	2.22