

Alma Mater Studiorum Università di Bologna  
Archivio istituzionale della ricerca

Efficient enantioresolution of aromatic  $\alpha$ -hydroxy acids with Cinchona alkaloid-based zwitterionic stationary phases and volatile polar-ionic eluents

This is the final peer-reviewed author's accepted manuscript (postprint) of the following publication:

*Published Version:*

Varfaj I., Protti M., Di Michele A., Macchioni A., Lindner W., Carotti A., et al. (2021). Efficient enantioresolution of aromatic  $\alpha$ -hydroxy acids with Cinchona alkaloid-based zwitterionic stationary phases and volatile polar-ionic eluents. ANALYTICA CHIMICA ACTA, 1180, 1-10 [10.1016/j.aca.2021.338928].

*Availability:*

This version is available at: <https://hdl.handle.net/11585/838681> since: 2021-11-16

*Published:*

DOI: <http://doi.org/10.1016/j.aca.2021.338928>

*Terms of use:*

Some rights reserved. The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. For all terms of use and more information see the publisher's website.

This item was downloaded from IRIS Università di Bologna (<https://cris.unibo.it/>).  
When citing, please refer to the published version.

(Article begins on next page)

1 **Efficient enantioresolution of aromatic  $\alpha$ -hydroxy acids with**  
2 ***Cinchona* alkaloid-based zwitterionic stationary phases and**  
3 **volatile polar-ionic eluents**

4  
5 Ina Varfaj <sup>a,1</sup>, Michele Protti <sup>b,1</sup>, Alessandro Di Michele <sup>c</sup>, Alceo Macchioni <sup>d</sup>,  
6 Wolfgang Lindner <sup>e</sup>, Andrea Carotti <sup>a,\*</sup>, Roccoaldo Sardella <sup>a,f,\*</sup>, Laura Mercolini <sup>b</sup>

7  
8  
9 <sup>a</sup> Department of Pharmaceutical Sciences, University of Perugia, Via Fabretti 48, 06123,  
10 Perugia, Italy

11 <sup>b</sup> Department of Pharmacy and Biotechnology (FaBiT), Alma Mater Studiorum, University of  
12 Bologna, Via Belmeloro 6, 40126, Bologna, Italy

13 <sup>c</sup> Department of Physics and Geology, University of Perugia, Via Pascoli 1, 06123, Perugia, Italy

14 <sup>d</sup> Department of Chemistry, Biology and Biotechnology, University of Perugia, Via Elce di Sotto  
15 8, 06123, Perugia, Italy

16 <sup>e</sup> Department of Analytical Chemistry, University of Vienna, W€ahringer Strasse 38, 1090,  
17 Vienna, Austria

18 <sup>f</sup> Center for Perinatal and Reproductive Medicine, University of Perugia, Santa Maria Della  
19 Misericordia University Hospital, 06132, Perugia, Italy

20  
21  
22 \* Corresponding author.

23 Department of Pharmaceutical Sciences, University of Perugia, Via Fabretti 48, 06123, Perugia, Italy.

24 E-mail addresses: andrea.carotti@unipg.it (A. Carotti), roccaldo.sardella@unipg.it (R. Sardella).

25 <sup>1</sup> Ina Varfaj and Michele Protti contributed equally to this work.

26

27 **Highlights**

28

29 • ZWIX(-) allows the enantioresolution of the three aromatic  $\alpha$ -hydroxy acids.

30

31 • The optimized polar-ionic conditions are fully compatible with MS detectors.

32

33 • The developed LC method can be used to study biological matrices with MS detectors.

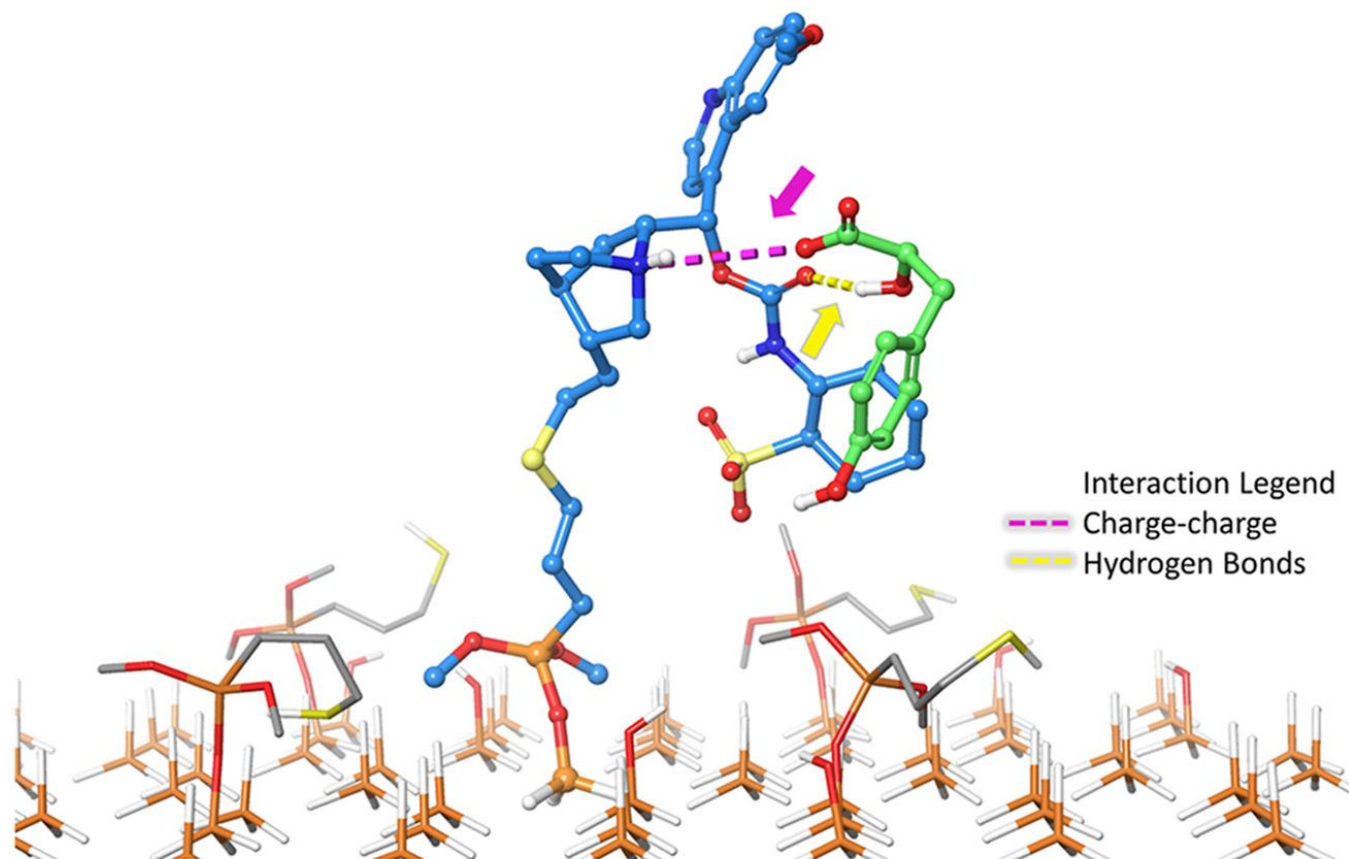
34

35 • Combining in silico simulations and ECD analyses is useful to derive the EEO.

36

37 • The retention mechanism can be explained with molecular dynamic simulations.

38



Interactions engaged by the CSP 1 (cyan sticks) and (S)-3 (green sticks)

41 **ABSTRACT**

42 Single enantiomers of mandelic acid (1), 3-phenyllactic acid (2), and 3-(4-hydroxyphenyl)lactic acid (3) are the  
43 subject of many fields of investigation, spanning from the pharmaceutical synthesis to that of biocompatible  
44 and biodegradable polymers, while passing from the interest towards their antimicrobial activity to their role  
45 as biomarkers of particular pathological conditions or occupational exposures to specific xenobiotics. All  
46 above mentioned issues justify the need for accurate analytical methods enabling the correct determination  
47 of the individual enantiomers. So far, all the developed liquid chromatography (LC) methods were not or  
48 hardly compatible with mass spectrometry (MS) detection. In this paper, a commercially available Cinchona-  
49 alkaloid derivative zwitterionic chiral stationary phase [that is, the CHIRALPAK® ZWIX(-)] was successfully used  
50 to optimize the enantioresolution of compounds 1–3 under polar-ionic (PI) conditions with a mobile phase  
51 consisting of an acetonitrile/methanol 95/5 (v/v) mixture with 80 mM formic acid. With the optimized  
52 conditions, enantioseparation and enantioresolution values up to 1.46 and 4.41, respectively, were obtained.  
53 In order to assess the applicability of the optimized enantioselective chromatography conditions in real-life  
54 scenarios and on MS-based systems, a proof-of-concept application was efficiently carried out by analysing  
55 dry urine spot samples spiked with 1 by means of a LC-MS system. The (S)<(R) enantiomer elution order (EEO)  
56 was established for compounds 1 and 2 by analysing a pure enantiomeric standard of known configuration.  
57 This was not possible for 3 because not commercially available. For this compound, the same EEO was  
58 identified applying a procedure based on ab initio time-dependent density-functional theory simulations  
59 coupled to electronic circular dichroism analyses. Moreover, a molecular dynamics simulation unveiled the  
60 role of the phenolic OH in compound 3 in the retention mechanism.

61  
62 **KEYWORDS:**

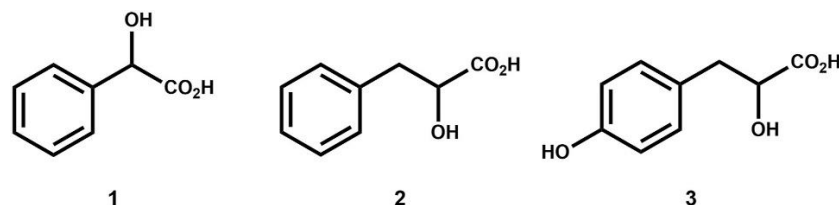
63 Ab-initio simulations; Aromatic  $\alpha$ -hydroxy acids; Dry urine spots; Electronic circular dichroism;  
64 Enantioresolution; MS-Compatible conditions.

65 **INTRODUCTION**

66

67 Mandelic acid (1), 3-phenyllactic acid (2), and 3-(4-hydroxyphenyl)lactic acid (3) (Fig. 1) are aromatic  $\alpha$ -  
68 hydroxy acids, with compounds 2 and 3 belonging to the class of phenyl propionic acids.

69



71

72 **Fig. 1.** Structure of the compounds investigated in the study: (1) mandelic acid; (2) 3-phenyllactic acid;  
73 (3) 3-(4-hydroxyphenyl)lactic acid.

74

75 Single enantiomers of compounds 1–3 are versatile chiral building blocks for the large-scale production of  
76 numerous active pharmaceuticals ingredients including semi-synthetic penicillins, cephalosporins and other  
77 antibiotics [[1], [2], [3], [4]], antitumor [5,6] and antiobesity agents [7], just to cite some. The three  
78 molecules are also very well-known (in an enantiomerically specific manner) for their antimicrobial activity  
79 [8,9], as well as for their use in the synthesis of biocompatible and biodegradable polymers also for  
80 promising biomedical applications [10,11].

81

82 Various approaches have been developed so far for the preparation of the enantiopure form of compounds  
83 1–3. These approaches include traditional organic synthesis methods, as well as enzymatic and biological  
84 routes [9,12,13]. In this scenario, over the last two decades, both biocatalytic asymmetric synthesis and  
85 fermentation processes have gained great interest both in industry and academia owing to the high  
86 efficiency, simple operation, environment-friendly nature and, in particular, excellent stereoselectivities  
87 [9,12,13]. Also importantly, the enantiomers of compounds 1–3 are often measured in biological matrices  
88 such as plasma and urine as biomarkers of particular pathological conditions (including phenylketonuria,  
89 hyperphenylalaninemia, tyrosinemia, gut microbial alterations, etc.) [14,15] as well as of environmental and  
90 occupational exposures to specific xenobiotics (such as styrene and ethylbenzene) [[16], [17], [18]].

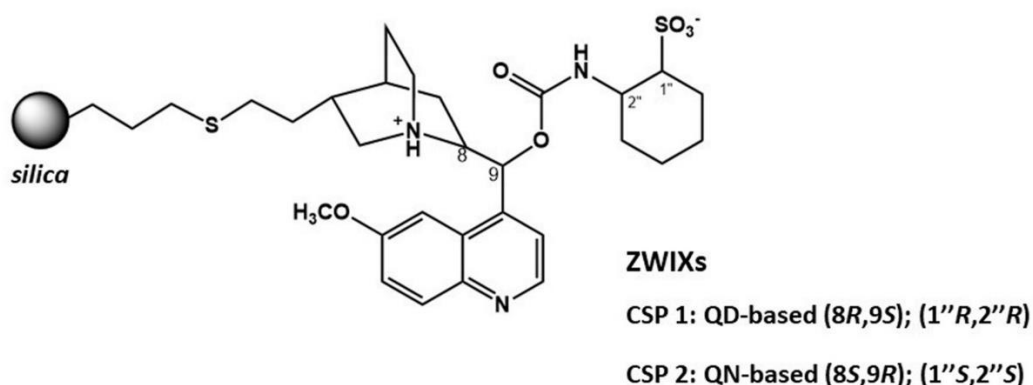
91

92 All above mentioned issues justify the need for accurate analytical methods enabling the correct  
93 determination of the individual enantiomers. So far, various direct enantioselective chromatography  
94 methods with commercially available chiral stationary phases (CSPs) have been developed for this aim.  
95 Accordingly, efficient enantioselective liquid chromatography (LC) analyses were performed with  
96 polysaccharide- [9,[19], [20], [21], [22]], glycopeptide- [23,24], protein- [25] and ligand-exchange-based [26]  
97 CSPs. However, all these methods were not or hardly compatible with mass spectrometry (MS) detection.

98

99 In order to fulfil this gap, we have developed the first LC method fully compatible with MS detectors. This

96 efficient enantioselective LC method relies upon the use of a polar-ionic (PI) mobile phase in combination  
97 with a zwitterionic CSP operating as an anion-exchanger. This zwitterionic CSP (CSP 1, Fig. 2) consists of a  
98 Cinchona-alkaloid derivative type chiral selector (SO), which has proven to produce enantioselectivity for  
99 many ionic and ionizable analytes under the most relevant elution regimes for LC applications [[27], [28],  
100 [29]]. Since commercial enantiopure standards are unavailable for compound 3, its enantiomeric elution  
101 order (EEO) in the optimized mobile phase conditions has been obtained with the application of a well-  
102 established method based on *ab initio* time-dependent density-functional theory (TD-DFT) simulations  
103 coupled to electronic circular dichroism (ECD) analyses [30,31]. Finally, in order to prove the compatibility  
104 of our method with MS detectors, dried urine spot (DUS) microsamples [32,33] spiked with mandelic acid  
105 (1) have been extracted and efficiently analysed by means of an ultra-high performance liquid  
106 chromatography (UHPLC)-MS system exploiting the optimized enantioselective chromatography conditions.  
107



108  
109  
110 **Fig. 2.** Structure of zwitterionic CSPs operating according an ion-exchange mechanism. The two CSPs belong  
111 to the family of Cinchona alkaloid-based enantio recognition materials and are commercialized by Chiral  
112 Technology Europe (Strasbourg, France) under the trade names CHIRALPAK® ZWIX(-) (CSP 1) and  
113 CHIRALPAK® ZWIX(+) (CSP 2).  
114

## 115 2. MATERIAL AND METHODS

### 116 2.1. Chemicals

117 All the reagents and solvents used in the study were of analytical grade. Acetonitrile (ACN), methanol  
118 (MeOH), formic acid (FA), acetic acid (AcOH), as well racemic mandelic acid (1), 3-phenyllactic acid (2), 3-(4-  
119 hydroxyphenyl)lactic acid (3) and 3-phenylpropionic acid - used as internal standard (IS) - were purchased  
120 from Merck Life Science (Merck KGaA, Darmstadt, Germany). The pure enantiomer of 1 and 2 were also  
121 from Merck Life Science. Water for HPLC analysis was purified with a New Human Power I Scholar water

122 purification system (Human Corporation, Seoul, Korea). For UHPLC-MS analysis, MS-grade ACN, MeOH and  
123 FA were employed and were purchased from Merck Life Science. Whatman FTA™ DMPK-B IND cards for  
124 DUS sampling were purchased from Merck Life Science, while a Whatman (Maidstone, MA, USA) Harris Uni-  
125 Core Punch, 6.0 mm was used for punching the DUS discs out of the spotting cards.

## 127 2.2. Instrumentations

128 The HPLC-UV analyses were performed on a Shimadzu HPLC equipped with a SCL-10Avp system controller,  
129 two LC-10AD high pressure binary gradient delivery systems, a SPD-10A variable-wavelength UV-Vis  
130 detector, and a Rheodyne 7725i injector with a 20 µL stainless steel loop. The enantioselective analyses  
131 were carried out with the CHIRALPAK® ZWIX(-) (CSP 1, Fig. 2) and CHIRALPAK® ZWIX(+) (CSP 2, Fig. 2) (150  
132 mm × 4.0 mm I.D, 120 Å pore size, 3 µm particle diameter) columns kindly provided by Chiral Technologies  
133 Europe (Strasbourg, France). All the analyses were performed at a 0.2 mL min<sup>-1</sup> eluent flow rate. The  
134 column temperature was fixed at 25 °C with a Grace (Sedriano, Italy) heater/chiller (Model 7956R)  
135 thermostat. A 254 nm detection wavelength was selected for the analyses. Acetone was selected as the  
136 unretained marker to evaluate the chromatographic parameters.

137 An ultra-high performance liquid chromatography coupled to single-quadrupole mass spectrometry  
138 (UHPLC-MS) system was exploited in order to assess the applicability of the optimized enantioselective  
139 chromatography conditions on MS-based systems and to obtain a proof-of-concept application by analysing  
140 spiked DUS samples. The system was composed of a UHPLC Vanquish pump, Vanquish Autosampler,  
141 Vanquish column compartment, and ISQ EC single-quadrupole mass spectrometer (Thermo Fisher Sci.,  
142 Waltham, MA, US), while data elaboration was carried out by means of Thermo Fisher Scientific Dionex  
143 Chromeleon 7.3 Chromatography Data System software. Enantioselective separations were obtained on the  
144 same CHIRALPAK® ZWIX(-) (CSP 1) column previously described, a 0.2 mL min<sup>-1</sup> flow rate and 20 µL  
145 injection volume; the autosampler needle was washed with 10% (v/v) MeOH (10 s) after each sample  
146 injection. Isocratic mobile phase consisted of a mixture of ACN/MeOH 95/5 (v/v) with 80 mM FA. Optimized  
147 mass spectrometric parameters were the following: vaporizer temperature (VT), 117 °C; ion transfer tube  
148 temperature (ITT), 300 °C; sheath gas pressure (SGP), 30 psig; auxiliary gas pressure (AGP), 3 psig; sweep  
149 gas pressure (SWGp), 0.5 psig. Negative ionisation mode was exploited, which resulted in extracted  
150 mandelic acid (1) chromatograms at m/z 151.1. Column and autosampler temperatures were maintained at  
151 25 °C and 10 °C, respectively.

152 The ECD spectra were recorded by a Jasco J-810 Spectropolarimeter (Jasco Corporation, Tokyo, Japan) at 25  
153 °C, using 10 mm quartz cell. The samples were solubilized in MeOH and analysed in the global spectral  
154 range of 210–400 nm.



155  
156  
157  
158  
159  
160  
161  
162  
163  
164  
165  
166  
167  
168  
169  
170  
171  
172  
173  
174  
175  
176  
177  
178  
179  
180  
181  
182  
183  
184  
185  
186  
187

## **2.3. Computational studies**

### **2.3.1. Theoretical ECD spectra simulations**

Compounds 1–3 were built by the Maestro interface (Schrödinger, LLC, New York, NY, 2020) present in the Schrödinger Suite 2020-2; Ligprep Protocol set at the default options was adopted to assign the correct protonation state. MMFF94s force field was used to perform a conformational search with the MacroModel module (Schrödinger, LLC, New York, NY, 2020) executing 200 steps with the “Mixed torsional/Low-mode sampling” using water as solvent and retaining at most 50 conformers, lying in a window of 5.0 kcal mol<sup>-1</sup> from the global minimum energy. The torsional sampling involved either multiple Monte Carlo minimum searches for global exploration, and the low mode conformational search allowed for automatic local exploration. The conformers that exceeded the threshold of 0.5 Å of the maximum atom deviation for any pair of corresponding atoms were considered to be different. Using the same settings applied in a recently published paper to simulate the ECD spectra of compound 1 [34], the resulting conformers were all submitted to a quantum mechanical energy optimization using the wB97X-D as DFT and the 6–311++G\*\*. Finally, the level of accuracy was set to Ultrafine (iacc = 1) in the Jaguar module (Schrödinger, LLC, New York, NY, 2020) [[35], [36], [37], [38]]. A RMSD threshold value of 0.01 Å for heavy atoms was applied to eliminate the high-lying or redundant conformers. The theoretical chiroptical properties of all the compounds were determined using a standard protocol for stereochemical characterization using TD-DFT calculations [30]. The sTD-DFT [39] calculations were carried out using the ORCA 4.1.2 software [40] using the wB97X-D3 as DFT and the 6–311++G\*\* basis set. The 50 lowest energy electronic transitions of each optimized conformer were used to calculate the theoretical values of oscillator strength ( $f_j$ ), rotational strength in dipole velocity formalism ( $R_j$ ), and excitation energy (expressed as wavelength,  $\lambda_j$ ). By approximation of  $f_j$  and  $R_j$  values to Gaussian bands with a  $\sigma$  value of 0.3 eV [41] the theoretical spectra of the optimized conformers were then derived. The weighted average of the contribution of all conformers according to their Boltzmann equilibrium populations at 298.15 K and 1 atm, based on free energy values ( $G$ ), was used to derive the theoretical ECD spectra of the compound and compared to the experimental spectra. This last step was performed using the SpecDis software [42]. The in silico spectra obtained by the different basis set used were compared with the experimental outcome, and the one showing the most similar profile was then selected for the EEO determination.

### **2.3.2. Molecular dynamics simulations**

The Maestro interface (Schrödinger, LLC, New York, NY, 2020) present in the Schrödinger Suite 2020-2 was used to reproduce the chromatographic environment. As reported in the previous work [43], a cubic box

188 was built with a 30 Å side length. For a realistic reproduction of the stationary phase environment, four 3-  
189 mercaptopropyl-functionalized silanols (~1.97 mol m<sup>-2</sup>), eight free silanols (~8.0 mol m<sup>-2</sup>) and forty-five  
190 silicon atoms were considered for each grafted selector (SO) unit (~0.5 mol m<sup>-2</sup>), at the base of the box. All  
191 the silicon atoms in the base layer were set frozen during the molecular dynamics. The box was solvated  
192 with ACN/MeOH 95/5 (v/v). The simulations were performed in the canonical ensemble at 298 K. The  
193 temperature in the simulation cell was maintained constant through use of a Nosé-Hoover thermostat  
194 [44,45]. All the other parameters in the simulation study were left to default values in the Desmond  
195 Molecular Dynamics System present in the Schrödinger Suite 2020-2 [46]. The production run produced  
196 1000 frames during the 300 ns dynamics, with an integration time of 2 fs.

#### 197 198 **2.4. Preparation of dry urine spots (DUSs) and UHPLC-MS analysis**

199 Urine samples, used as blank matrix, were obtained from healthy volunteers. Aliquots of 200 µL were  
200 spiked with 10 µL of standard mixtures containing 1 and IS to obtain urine concentrations of 100 ng mL<sup>-1</sup>, 1  
201 µg mL<sup>-1</sup> and 100 µg mL<sup>-1</sup> of 1 and a fixed IS concentration of 100 ng mL<sup>-1</sup>. Then, the obtained fortified  
202 urine was subjected to DUS sampling and pretreatment before UHPLC-MS analysis. Aliquots of 10 µL of  
203 urine were transferred onto a Whatman FTA™ DMPK-B IND card by means of micropipetting; the obtained  
204 spots were left to dry for 1 h at room temperature, then stored in the dark with suitable desiccant until  
205 pretreatment and analysis. At the time of analysis, a 10-mm diameter circle was punched out from the card  
206 with a puncher and placed into a vial with 250 µL of 80 mM FA in MeOH, subjected to ultrasound-assisted  
207 extraction (UAE) at room temperature for 10 min and centrifuged at 4000 rpm for 5 min at 4 °C. The  
208 supernatant was brought to dryness under a gentle N<sub>2</sub> stream, re-dissolved with 100 µL of an ACN/MeOH  
209 95/5 (v/v) mixture with 80 mM FA and analysed by UHPLC-MS without the need for further treatment.  
210 Resulting chromatograms were checked and compared with chromatograms from 1 standard solutions,  
211 then the overlapping of retention times and the correspondence of chromatographic parameters were  
212 verified.

### 213 214 **3. RESULTS AND DISCUSSION**

#### 215 **3.1. Enantioseparation study of compounds 1–3**

216 One of the main advantages of using CSP 1 and CSP 2 (Fig. 2) is their well-documented flexibility to behave  
217 as cation-exchangers (CXs) for the enantioseparation of chiral bases [47,48], as anion-exchanger (AXs) for  
218 the enantioseparation of chiral acids [27,49,50], and as zwitterionic ion-exchangers for the  
219 enantioseparation of ampholytic compounds [28,51,52].

220 CSP 1 and CSP 2 are commercially available as CHIRALPAK® ZWIX(-) and CHIRALPAK® ZWIX(+) (Chiral

221 Technology Europe, Strasbourg – France), and present the following structural characteristics: in CSP 1, QD  
222 is fused via a carbamoyl group with (R,R)-trans-2-aminocyclohexanesulfonic acid (R,R-ACHSA), whereas in  
223 CSP 2 QN is identically fused with (S,S-ACHSA); for the chiral selectors (SOs) incorporated in CSP 1 and CSP  
224 2, the absolute configuration of N1, C3 and C4 is the same (that is, 1S,3R,4S), while an opposite  
225 configuration is present at C8 and C9 of the Cinchona scaffold (that is, 8R, 9S in CSP 1, and 8S, 9R in CSP 2).  
226 Moreover, CSPs 1 and 2 feature opposite configuration also at C1" and C2" in the ACHSA ring, which is the  
227 reason why these two CSPs very often display a so-called "pseudo-enantiomeric" behaviour in terms of  
228 their chiral recognition ability [49,[53], [54], [55]].

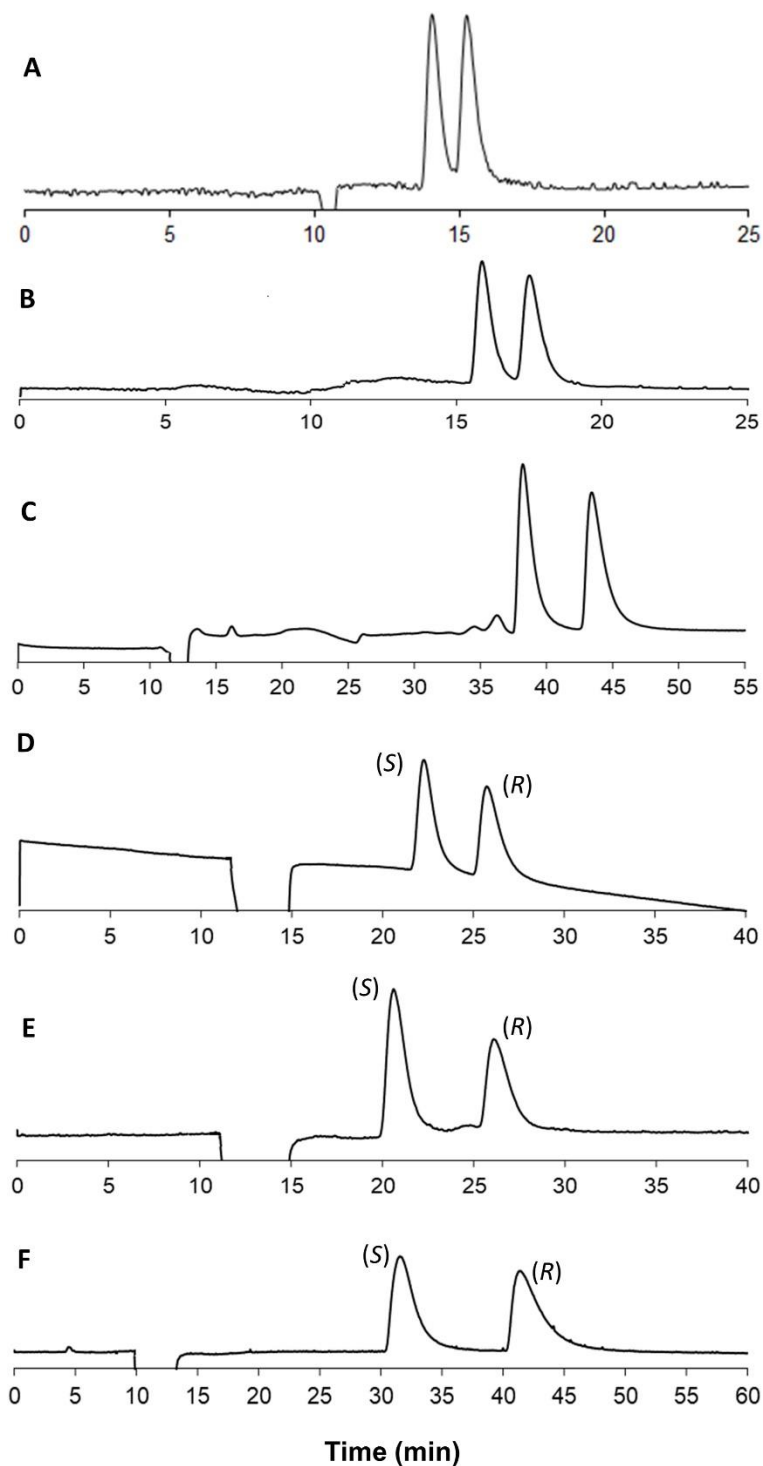
229 The use of polar-ionic (PI) eluents was here preferred over reversed-phase (RP) ones since the former often  
230 produce higher enantioselectivities as a result of the following mechanisms. PI mobile phases are capable  
231 to attenuate or even inactivate non-enantioselective interactions (both hydrophobic and other types of  
232 interactions) with the stationary phase functionalities [52,54,56]. Moreover, a strong solvation of ionic  
233 selectands (SAs) and zwitterionic SOs takes place under RP conditions, which in turn reduces the strength of  
234 the ion pairing process with a detrimental effect on enantioselectivity. Furthermore, the solvation by  
235 aqueous eluents might mitigate or even abolish non-ionic but stereo discriminating interactions, with a  
236 negative impact on the overall enantioselectivity extent.

237 Due to the IMCI effect, the elution of anionic analytes might in principle occur even without any mobile  
238 phase counterion [28]. However, this possibility is disadvantageous in practice since it may lead to  
239 extremely long retention times [28]. Therefore, acidic additives (often used in combination with basic  
240 additives or replaced by buffers) are added to the eluent as counter-ions to trigger the enantioseparation  
241 process. The incorporation of acids in the eluent ensures, inter alia, the protonated state of the  
242 quinuclidine nitrogen, which is a fundamental pre-requisite for the ion-pair and ion-exchange processes.

243 A solution consisting of MeOH with 160 mM AcOH was used as initial mobile phase. The use of the highly  
244 volatile and more MS compatible FA was avoided for its well-known relatively fast reaction with MeOH  
245 yielding FA methyl ester [52,56]. With that mobile phase and CSP 1, only compound 1 was partially  
246 separated (Fig. 3A), while base-line resolution was obtained for compounds 2 and 3 (Table 1, entries 1, 8  
247 and 10). CSP 2 did not distinguish the enantiomers of 1, while exhibited good enantioseparation capability  
248 for the other two analytes (data not shown). The two zwitterionic SOs are diastereomeric in nature and  
249 therefore characterized by geometrically and conformationally oriented interaction sites, such as the  
250 carbamate group (mostly involved in H-bonding- and dipole-dipole-interactions) and the quinoline moiety  
251 (mostly participating in  $\pi$ - $\pi$ -interactions). These structural elements are together or separately involved in  
252 the overall enantiorecognition process. The different chromatographic behaviour exhibited by CSP 1 and  
253 CSP 2 can be rationally explained on this basis [47]. CSP 1 was therefore selected for the following

254 optimization steps aimed at improving the performance on compound 1.

255



256

257

258

259

260

**Fig. 3.** Chromatograms of compounds 1–3 obtained under PI conditions with CSP 1. Mobile phase conditions can be retrieved from Table 1 (A) cpd 1, entry 1; (B) cpd 1, entry 2; (C) cpd 1, entry 6; (D) cpd 1, entry 8; (E) cpd 2, entry 10; (F) cpd 3, entry 12. The EEO has been reported in the best chromatographic conditions.

**Table 1.** Chromatographic performances obtained for compounds 1–3 with CSP 1.

Compound	Entry	Mobile phase <sup>a</sup>	Chromatographic parameters					
			$k_1$	$k_2$	$N_1$	$N_2$	$\alpha$	$R_s$
<b>1</b>	1	A	0.74	0.89	4568	4422	1.20	1.37
	2	B	0.96	1.17	4466	4059	1.21	1.59
	3	C	0.83	1.01	3354	2655	1.23	1.32
	4	D	0.91	1.13	4314	4024	1.24	1.74
	5	E	1.45	1.72	4514	4280	1.19	1.73
	6	F	3.73	4.37	6354	5398	1.17	2.44
	7	G	2.95	3.68	873	454	1.25	1.04
	8	H	1.76 (S)	2.18 (R)	3092	2862	1.24	1.97
<b>2</b>	9	A	0.37	0.77	2438	2793	2.06	3.23
	10	H	1.55 (S)	2.23 (R)	1982	2283	1.44	2.72
<b>3</b>	11	A	0.27	0.65	3159	3179	2.39	3.64
	12	H	2.90 (S)	4.12 (R)	1447	1688	1.42	2.69

<sup>a</sup> Composition: (a) MeOH with 160 mM AcOH; (b) MeOH with 80 mM AcOH; (c) MeOH/ACN 98/2 (v/v) with 80 mM AcOH; (d) MeOH/ACN 95/5 (v/v) with 80 mM AcOH; (e) MeOH/ACN 90/10 (v/v) with 80 mM AcOH; (f) ACN with 80 mM AcOH; (g) ACN/MeOH 95/5 (v/v) with 80 mM AcOH; (h) ACN/MeOH 95/5 (v/v) with 80 mM FA. The EEO has been reported in the best chromatographic conditions.

Testing different additive concentrations can be a useful tool to adjust column performance, e.g., to slow analysis with improved enantioresolution. When AcOH concentration was reduced from 160 mM (Table 1, entry 1) down to 80 mM (Table 1, entry 2), retention factors significantly increased in accordance to a typical AX process [27,49] and the stoichiometric displacement model [28,51,[56], [57], [58]]. At the same time, the  $\alpha$  value remained nearly unchanged, suggesting a negligible effect of counterion on other tentative binding increments mainly responsible for enantioselectivity (namely H-bond and van der Waals/steric interactions). Instead, resolution factors ( $R_s$ ) increased with the reduction of the eluent ionic strength, as a result of the increased retention of both enantiomers. With the lower AcOH concentration, base-line separation ( $R_s$  of 1.59; Table 1, entry 2) (Fig. 3B) of **1** was obtained.

In order to further improve the chromatographic performance, we scrutinized the impact of the combination of a protic and an aprotic eluent component. Accordingly, we continued to use MeOH as a protic solvent (which can suppress H-bonding interactions), this time in combination with a low amount of

281 ACN, which is an aprotic solvent known to support ionic interactions but to interfere with aromatic ( $\pi$ - $\pi$ -  
282 stacking) interactions [59]. In order to optimize the ratio of these two solvents, three different binary  
283 eluents were evaluated (Table 1, entries 3–5), while keeping the AcOH concentration fixed at 80 mM. As  
284 expected, a clear increase of the retention was observed with increasing concentrations of ACN from 2 up  
285 to 10% (v). This behaviour can be explained by considering the reduced solvation power of ACN leading to  
286 the enforcement of the electrostatic interactions between the anionic group of the analyte and the  
287 protonated quinuclidine moiety of the SO. However, the presence of an aprotic component in the eluent  
288 did not significantly enhance the separation properties of the system (Table 1, entries 3–5), thus indicating  
289 that H-bonding interactions are important for analyte retention, whilst these seem not to support the chiral  
290 recognition process. Conversely, increasing the ACN concentration in the eluent led to an improvement of  
291 RS values as a result of the higher retention and enhanced efficiency.

292 Replacing MeOH with ACN, while keeping constant the acid concentration in the eluent, led to the  
293 formation of a thinner solvation shell around the charged moieties of both SO and SA, thus amplifying the  
294 strength of the electrostatic attractions, with a consequent elongation of the retention time (Table 1,  
295 entries 2 and 6) [28,47,49,55,60]. The longer retention times recorded with the aprotic mobile phase can be  
296 plausibly attributed to a less effective contribution of the IMCI effect. This outcome is in strict accordance  
297 with the recognized ability by ACN to promote stronger intermolecular SO-SA interactions disfavouring  
298 intramolecular interactions. A mobile phase consisting of only ACN (plus ionic additives) is usually not  
299 recommended as it reduces the solubility of many ionizable solutes. As a consequence, these compounds  
300 could partially precipitate on the top of the column and a slow dissolution of this portion of solute takes  
301 place only with the passage of large volumes of mobile phase. Severe peak tailing is often promoted in such  
302 circumstances. This might explain the stronger peak asymmetry observed with the ACN- (tailing factor  
303 measured at 10% of peak height equal to 2.2 and 2.4 for the first and the second eluted enantiomer,  
304 respectively; Fig. 3C) over the MeOH-based (tailing factor measured at 10% of peak height equal to 1.7 for  
305 both enantiomers; Fig. 3B) eluent. The stronger tailing observed with ACN was accompanied by the  
306 remarkable gain in resolution (Table 1, entries 2 and 6), ascribable to the higher retention and improved  
307 efficiency. Based on this result, and aimed at reducing the elution time while keeping safe the quality of the  
308 enantioseparation process, also in terms of peak shape, 5% (v) of MeOH was added to ACN with AcOH (80  
309 mM). With this eluent system an expected reduction of the retention time turned out along with a sensitive  
310 deterioration of the kinetic properties of the system (Table 1, entry 7). Following this observation, and  
311 aware that the type and concentration of acidic additive can have a profound impact on the retention  
312 profile and the quality of the enantioseparation process [27,50,55], AcOH was replaced with FA at the same  
313 concentration (80 mM). With this eluent, no problems with mobile phase stability actually exist due to the

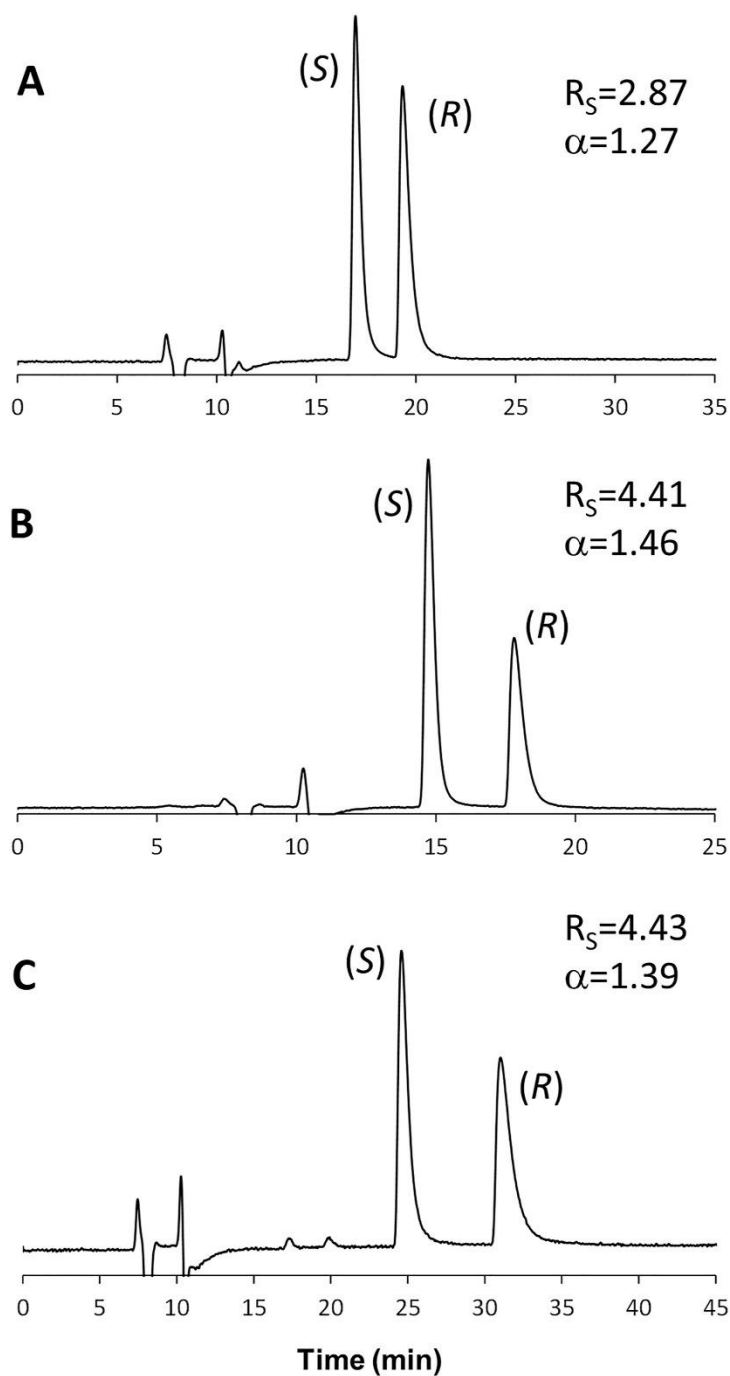
314 high content of ACN, making the mobile phase more suited to MS detection systems. In the last eluent,  
315 excellent chromatographic performances were obtained for compound 1 (Table 1, entry 8; Fig. 3D), which  
316 stimulated us to test these conditions also for the analysis of 2 and 3. Also for these two compounds, very  
317 successful results were obtained under the last PI eluent tested (Table 1, entries 10, and 12; Fig. 3E and 3F,  
318 respectively for compound 2, and 3).

319 It has been recently documented [59] that FA and AcOH can differently contribute to the overall  
320 enantio-recognition event with the CSPs employed in this study. Indeed, these two acids have been  
321 demonstrated to participate differently in the formation and composition of the solvation shells of the CSPs  
322 and SAs. In spite of their non-chiral nature, the acidic additives display an intimate participation to the  
323 chromatographic process as a whole. Indeed, these additives are capable to affect the conformation of the  
324 SO and SA, in turn modifying the orientation of the complementary interacting functional groups on SO and  
325 SA. The higher retention in the presence of AcOH (Table 1, entry 7) over FA (Table 1, entry 8) can be  
326 explained with the ability by the former to produce solvation shells of smaller dimension on CSP 1,  
327 ultimately leading to a stronger Coulomb attraction and higher enantiomer retention [59]. On the other  
328 side, the highly polar FA is better adsorbed onto the CSP surface, thereby implying a remarkable change of  
329 its retention properties.

330 The poor kinetic properties produced by eluent "g" (Table 1, entry 7) can be tentatively explained by a  
331 competition between AcOH and MeOH in the solvation layer of the CSP, which can impair the  
332 conformational flexibility of the SO unit [59].

333 Very intriguingly, a rather different chromatographic behaviour was found for all of the three compounds  
334 when solubilized in ACN and analysed with the optimal [ACN/MeOH 95/5 (v/v) with 80 mM FA] mobile  
335 phase. A sensitive reduction of the retention time was always observed, accompanied by very appreciable  
336 enantio-separation and enantio-resolution factors (Fig. 4). In a previous paper [61], some of us already  
337 highlighted that the sample diluent may have a deep effect on the enantio-separation profile with ZWIX-  
338 type CSPs under PI elution conditions. Ideally, for Chiralpak ZWIXs used under PI condition, the sample  
339 diluent should have low elution strength, and therefore plain ACN should theoretically represent one of the  
340 best options. However, further investigations are required to rationalize the effect produced by ACN as  
341 sample diluent, which is out of the scope of the present paper.

342



**Fig. 4.** Chromatograms of compounds (A) 1, (B) 2, (C) 3, obtained with the optimal [ACN/MeOH 95/5 (v/v) with 80 mM FA] mobile phase after the solubilization in plain ACN.

The higher retention of compound 3 under the applied eluent conditions with CSP 1 can be tentatively explained with a stabilizing H-bonding interaction by the phenolic OH group (see section 3.2. for further details).



351 The chromatogram of 2 depicted in Fig. 3E reveals the non-racemic nature of this analyte, although it was  
352 purchased as such. The analysis of this compound was performed under the same eluent conditions with  
353 CSP 2 in order to verify this issue. Thanks to the pseudo-enantiomeric behaviour often exhibited by the two  
354 zwitterion-type CSPs, a reversal of the elution order was observed for compound 2 when analysed with the  
355 CSP carrying the quinine scaffold (Fig. S1, Supplementary Material). The scalemic nature of sample 2 was  
356 tentatively ascribed to an incorrect storage of the sample powder in our laboratory.

357 Mobile phase "h" was also used in combination with CSP 2. As a result, only compound 2 was almost base-  
358 line separated, while a hint of separation turned out for 1 and co-elution for the enantiomers of 3.

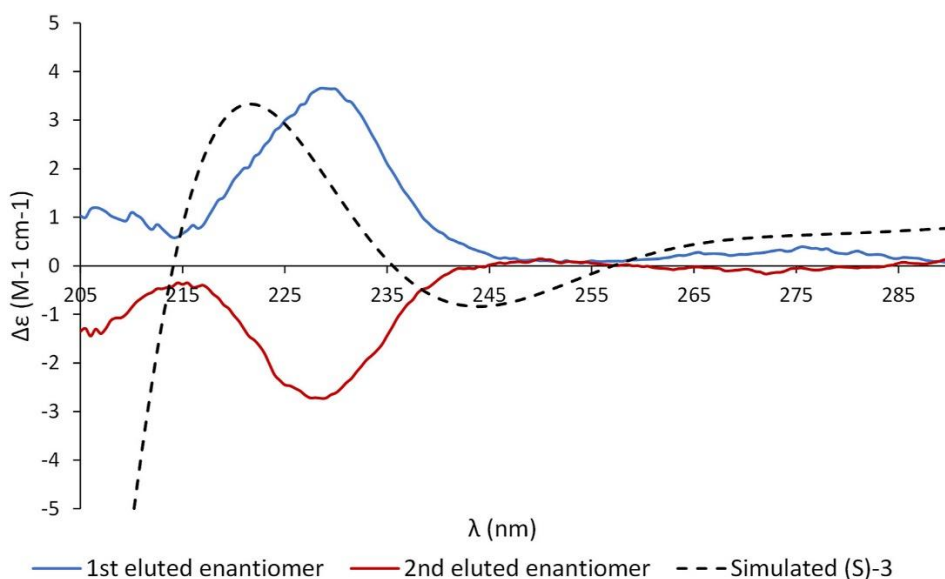
359 The (S)<(R) enantiomer elution order (EEO) was established for compounds 1 and 2 injecting a pure  
360 enantiomeric standard of known configuration. This was not possible for 3 because not commercially  
361 available. For this compound, the same EEO was identified applying a well-established molecular modelling  
362 procedure described in detail in sections 2.3 Computational studies, 3.2 Assignment of the absolute  
363 configuration through ECD studies and molecular dynamics simulations.

### 364 **3.2. Assignment of the absolute configuration through ECD studies and molecular dynamics simulations**

365 Due to the lack of pure enantiomeric standards of known stereochemistry for compound 3, an indirect  
366 protocol was applied to establish the enantiomer elution order (EEO) under the optimized eluent  
367 conditions. Accordingly, based on a well-established protocol [30,31], ECD studies were coupled to ab initio  
368 TD-DFT simulations. Experimental ECD spectra of the two enantiomers of compound 3 after their off-line  
369 collection with the CSP 1 have been retrieved.

370 As readily evident from the ECD spectra displayed in Fig. 5, the two isolated peaks exhibit specular Cotton  
371 effects typical of enantiomeric compounds, with the main band centred at around 230 nm. The ECD  
372 spectrum of the first eluted peak is well mimicked by the TD-DFT theoretical spectrum of (S)-3 obtained by  
373 the use of the wB97X-D functional with the 6-311++G\*\* basis set.

374  
375



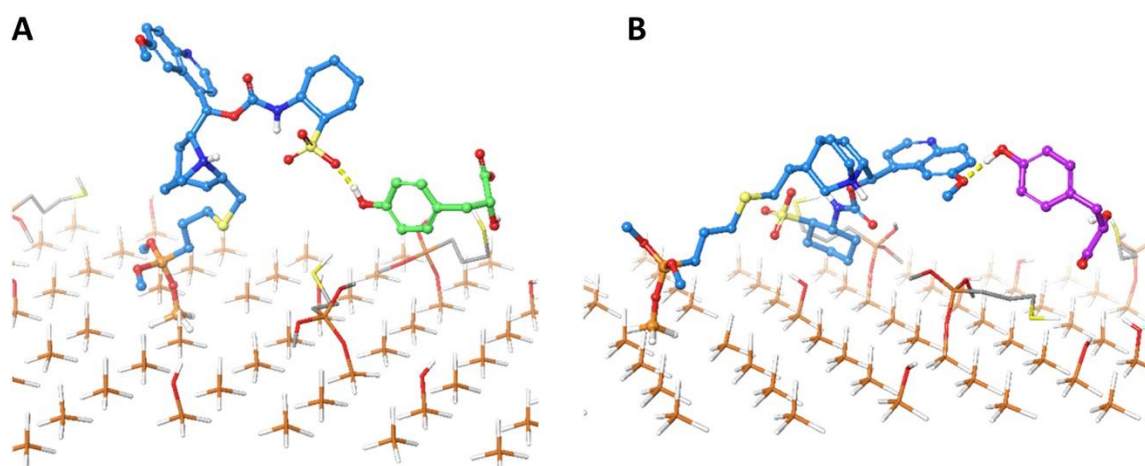
**Fig. 5.** Experimental ECD spectra of the first- (blue line) and second-eluted (red line) enantiomeric fraction of 3. The theoretical spectrum of the (S)-enantiomer is reported as black dashed-line. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

In order to confirm the correctness of the sTD-DFT settings used for the assignment of the EEO of compound 3, the same protocol was also applied to calculate the theoretical ECD spectrum for the enantiomers of compounds 1 and 2 (Fig. S2, Supplementary Material). The ECD spectra of compounds 1 and 2 confirmed that the employed computational method is capable to successfully reproduce the Cotton effects for these two compounds. Moreover, the results obtained for the enantiomers of 1 and 2 are in strict accordance with those produced by other authors [34,62], in turn confirming the quality of our approach any longer.

The main positive Cotton effect at around 230 nm, that is a shared signature of the ECD spectra of both compounds 1 and 2, is also evident in the theoretical spectrum of (S)-3, supporting a safe conclusion about the EEO. Based on this result, the (S)-3 < (R)-3 can be deduced.

With respect to compounds 1 and 2, analyte 3 bears a unique feature that is a para-hydroxy moiety that was found to play a role in the retention mechanism. In order to investigate this aspect and with the additional aim to further support the indirect EEO assignment, a molecular dynamic run has been performed on both (S)- and (R)-3 enantiomers using a simulation box representing the chromatographic environment, as described in details in section 2.3.2. The monitoring of the H-bond established by the hydroxy group during the whole trajectory revealed that (R)-3 enantiomer interacts 48 times with the sulfonic acid moiety of the ZWIX(-) while the (S)-3 molecule only three times engages a hydrogen bond

399 with the methoxy group of the quinoline moiety of the selector (Fig. 6A and B, respectively). The obtained  
400 results are in line with the retention behaviour of this compound over the other two examined.  
401



402  
403  
404 **Fig. 6.** Exemplary frames of the H-bond interactions (yellow dashed lines) engaged by the CSP 1 (cyan sticks)  
405 and (A) the (S)-3 (green sticks) and (B) (R)-3 (magenta sticks). (For interpretation of the references to colour  
406 in this figure legend, the reader is referred to the Web version of this article.)  
407

### 408 3.3. Dried urine spot (DUS) analysis

409 In order to assess the applicability of the optimized enantioselective chromatography conditions in real-life  
410 scenarios and on MS-based systems, a proof-of-concept application was carried out by analysing DUS  
411 samples spiked with mandelic acid (1) by means of a UHPLC-MS system. Details on this subject are reported  
412 in section 2.4.

413 For this proof-of-concept application, it should be considered that, for the occupational exposure to  
414 styrene, the Biological Exposure Index (BEI) for mandelic acid is 800 mg g<sup>-1</sup> creatinine (corresponding to a  
415 concentration of mandelic acid of 8 µg mL<sup>-1</sup> urine, considering an average urinary creatinine concentration  
416 of 1 mg dL<sup>-1</sup>), according to the American Congress of Governmental Industrial Hygienists (ACGIH) [63]. On  
417 the other hand, physiological concentrations of mandelic acid in urine samples from workers not exposed  
418 to styrene were estimated to be in the order of magnitude of 25–250 ng mL<sup>-1</sup> [64].

419 In the present study, method sensitivity in terms of lower limit of quantitation (LLOQ) was evaluated based  
420 on international bioanalytical method validation guidelines [65] as the lowest concentration of 1 in DUS  
421 samples which can be quantified reliably, with an acceptable accuracy and precision, and corresponding to  
422 5 times the signal of a blank sample. The LLOQ value estimated for the methodology proposed herein was 5  
423 ng racemic 1 per mL urine, thus being well below the BEI limit value but also lower than physiological 1

424 urinary levels in non-exposed workers.

425 In Fig. 3S (Supplementary Materials), the ESI-UHPLC-MS chromatogram obtained from the analysis of a DUS  
426 sample spiked with rac-1 is shown.

#### 427 **4. CONCLUSIONS**

428  
429 In this paper we have demonstrated that the Cinchona-alkaloid derived zwitterionic CSPs are suitable  
430 materials for the enantioresolution of the three aromatic  $\alpha$ -hydroxy acids under investigation. The  
431 optimized chromatographic method based on the use of a volatile PI mobile phase makes it compatible  
432 with MS detection systems. The possibility to perform analysis by means of mass spectrometry opens the  
433 way to carry out important in-depth investigations in crucial fields such as biomarker and environmental  
434 monitoring and food safety assessment, just to cite some. In this framework, the possibility to combine the  
435 developed advanced chromatographic system to automated microsampling protocols and platforms for  
436 ultra-high performance liquid chromatography coupled to mass spectrometry analysis can make it easier to  
437 set-up high-throughput screening campaigns. This last point can be concretely pursued thanks to the  
438 possibility to efficiently scale the developed chromatographic method down to the same commercial  
439 columns of smaller dimensions.

440 Based on the encouraging results obtained in the present study, we intend to apply the developed method  
441 for the following purposes. The optimized chromatographic method coupled to the described DUS  
442 microsampling approach will be implemented (i) for workplace exposure controls aimed at feasibly and  
443 reliably monitoring the incidence of styrene and ethylbenzene vaporous in workroom environments  
444 (through the analysis of 1); (ii) to further investigate the possible use of compound 2 as a biomarker of both  
445 ovarian and cervical cancers; (iii) for in-depth investigations of specific tyrosinemic disorders (through the  
446 analysis of 3). Moreover, the developed chromatographic method will be applied to identify alimentary  
447 sources rich in (R)-2 being used as food and feed additives to limit microbial contaminations.

#### 448 449 **CRedit authorship contribution statement**

450 Ina Varfaj: Methodology, Investigation, Writing – original draft. Michele Protti: Methodology, Investigation,  
451 Writing – original draft. Alessandro Di Michele: Investigation. Alceo Macchioni: Writing – review & editing.  
452 Wolfgang Lindner: Writing – review & editing, Supervision. Andrea Carotti: Conceptualization,  
453 Methodology, Validation, Formal analysis, Writing – original draft, Data curation. Roccaldo Sardella:  
454 Conceptualization, Methodology, Validation, Writing – original draft, Supervision, Writing – review &  
455 editing, Project administration. Laura Mercolini: Conceptualization, Methodology, Validation, Writing –  
456 original draft, Supervision, Writing – review & editing, Project administration.

457

458 **Declaration of competing interest**

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

461

462 **REFERENCES**

463 [1] K. Tang, J. Yi, K. Huang, G. Zhang, Biphasic recognition chiral extraction: a novel method for separation of  
464 mandelic acid enantiomers, *Chirality* 21 (2009) 390e395.

465 [2] M. Terreni, G. Pagani, D. Ubiali, R. Fernandez-Lafuente, C. Mateo, J.M. Guis an, Modulation of  
466 penicillin acylase properties via immobilization techniques: one-pot chemoenzymatic synthesis of  
467 Cephmandole from Cephalosporin C, *Bioorg. Med. Chem. Lett* 11 (2001) 2429e2432.

468 [3] K. Ström, J. Sjögren, A. Broberg, J. Schnürer, *Lactobacillus plantarum* MiLAB 393 produces the  
469 antifungal cyclic dipeptides cyclo(L-Phe-L-Pro) and cyclo(LPhe- trans-4-OH-L-Pro) and 3-phenyllactic acid,  
470 *Appl. Environ. Microbiol.* 68 (2002) 4322e4327.

471 [4] S.K. Bhatia, P.K. Mehta, R.K. Bhatia, T.C. Bhalla, Optimization of arylacetonitrilase production from  
472 *Alcaligenes* sp. MTCC 10675 and its application in mandelic acid synthesis, *Appl. Microbiol. Biotechnol.* 98  
473 (2014) 83e94.

474 [5] A.D. Abell, J.W. Blunt, G.J. Foulds, M.H.G. Munro, Chemistry of the mycalamides: antiviral and  
475 antitumour compounds from a New Zealand marine sponge. Part 6.1e3 the synthesis and testing of  
476 analogues of the C(7)eC(10) fragment, *J. Chem. Soc. Perkin Transact. 1* (1997) 1647e1654.

477 [6] J.P. Surivet, J.M. Vatele, Total synthesis of antitumor *Goniothalamus styryllactones*, *Tetrahedron* 55  
478 (1999) 13011e13028. [7] J. Mill, K.K. Schmiegel, W.N. Shaw, US Patent 4391826 (1983).

479 [8] S.S. Chaudhari, D.V. Gokhale, Phenyllactic Acid: a potential antimicrobial compound in lactic acid  
480 bacteria, *J. Bacteriol. Mycol. Open Access* 2 (2016) 121e125.

481 [9] X. Luo, Y. Zhang, L. Yin, W. Zheng, Y. Fu, Efficient synthesis of d-phenyllactic acid by a whole-cell  
482 biocatalyst co-expressing glucose dehydrogenase and a novel d-lactate dehydrogenase from *Lactobacillus*  
483 *rossiae*, *3 Biotech* 10 (2020) 1e9.

484 [10] T. Fujita, H.D. Nguyen, T. Ito, S. Zhou, L. Osada, S. Tateyama, T. Kaneko, N. Takaya, Microbial monomers  
485 custom-synthesized to build true bio-derived aromatic polymers, *Appl. Microbiol. Biotechnol.* 97 (2013)  
486 8887e8894.

487 [11] H. Kawaguchi, C. Ogino, A. Kondo, Microbial conversion of biomass into biobased polymers, *Bioresour.*  
488 *Technol.* 245 (2017) 1664e1673.

489 [12] W. Mu, S. Yu, L. Zhu, B. Jiang, T. Zhang, Production of 3-phenyllactic acid and 4-hydroxyphenyllactic

490 acid by *Pediococcus acidilactici* DSM 20284 fermentation, *Eur. Food Res. Technol.* 235 (2012) 581e585.

491 [13] H. Wang, H. Fan, H. Sun, L. Zhao, D. Wei, Process development for the production of (R)-(-)-mandelic  
492 acid by recombinant *Escherichia coli* cells harboring nitrilase from *Burkholderia cenocepacia* J2315, *Org.*  
493 *Process Res. Dev.* 19 (2015) 2012e2016.

494 [14] Y. Yang, F. Liu, Y. Wan, Simultaneous determination of 4-hydroxyphenyl lactic acid, 4-hydroxyphenyl  
495 acetic acid, and 3,4-hydroxyphenyl propionic acid in human urine by ultra-high performance liquid  
496 chromatography with fluorescence detection, *J. Separ. Sci.* 40 (2017) 2117e2122.

497 [15] J. Liu, A. Yan, Y. Yang, Y.Q. Wan, Determination of 4-hydroxyphenyllactic acid in human urine by  
498 magnetic solid-phase extraction and high-performance anion-exchange chromatography with fluorescence  
499 detection, *Anal. Lett.* 50 (2017) 259e270.

500 [16] E. Mayatepek, C.K. Seppel, G.F. Hoffmann, Increased urinary excretion of dicarboxylic acids and 4-  
501 hydroxyphenyllactic acid in patients with Zellweger syndrome, *Eur. J. Pediatr.* 154 (1995) 755e756.

502 [17] F. Cosnier, H. Nunge, B. Cossec, L. Gate, Simultaneous determination of aromatic acid metabolites of  
503 styrene and styrene-oxide in rat urine by gas chromatography-Flame ionization detection, *J. Anal. Toxicol.*  
504 36 (2012) 312e318.

505 [18] J.Z. Wang, X.J. Wang, Y.H. Tang, S.J. Shen, Y.X. Jin, S. Zeng, Simultaneous determination of mandelic  
506 acid enantiomers and phenylglyoxylic acid in urine by high-performance liquid chromatography with  
507 precolumn derivatization, *J. Chromatogr. B Anal. Technol. Biomed. Life Sci.* 840 (2006) 50e55.

508 [19] A. Tekewe, S. Singh, M. Singh, U. Mohan, U.C. Banerjee, Development and validation of HPLC method  
509 for the resolution of drug intermediates: dl-3-Phenyllactic acid, dl-O-acetyl-3-phenyllactic acid and (±)-  
510 mexiletine acetamide enantiomers, *Talanta* 75 (2008) 239e245.

511 [20] B.R. Lukito, Z. Wang, B. Sundara Sekar, Z. Li, Production of (R)-mandelic acid from styrene, L-  
512 phenylalanine, glycerol, or glucose via cascade biotransformations, *Bioresour. Bioprocess.* 22 (2021) 2e11.

513 [21] Y. Zhu, Y. Wang, J. Xu, J. Chen, L. Wang, B. Qi, Enantioselective biosynthesis of L-phenyllactic acid by  
514 whole cells of recombinant *Escherichia coli*, *Molecules* 22 (2017) 1e11.

515 [22] I. Jerković, M. Roje, C.I.G. Tuberoso, Z. Marijanović, A. Kasum, M. Obradović, *Bioorganic Research*  
516 *of Galactites tomentosa* Moench. Honey extracts: enantiomeric purity of chiral marker 3-Phenyllactic acid,  
517 *Chirality* 26 (2014) 405e410.

518 [23] M. Shahnani, Y. Sefidbakht, S. Maghari, A. Mehdi, H. Rezadoost, A. Ghassempour, Enantioseparation of  
519 mandelic acid on vancomycin column: experimental and docking study, *Chirality* 32 (2020) 1289e1298.

520 [24] P. Jandera, M. Skavrada, K. Klemmová, V. Bačková, G. Guiochon, Effect of the mobile phase on  
521 the retention behaviour of optical isomers of carboxylic acids and amino acids in liquid chromatography on  
522 bonded Teicoplanin columns, *J. Chromatogr. A* 917 (2001) 123e133.

523 [25] E. Müller, O. Sosedov, J.A.D. Gr€oning, A. Stolz, Synthesis of (R)-mandelic acid and (R)-mandelic acid  
524 amide by recombinant E. coli strains expressing a (R)- specific oxynitrilase and an arylacetonitrilase,  
525 Biotechnol. Lett. 43 (2021) 287e296.

526 [26] I. Ohhira, S. Kuwaki, H. Morita, T. Suzuki, S. Tomita, S. Hisamatsu, S. Sonoki, S. Shinoda, Identification of  
527 3-Phenyllactic acid as a possible antibacterial substance produced by Enterococcus faecalis TH10, Biocontrol  
528 Sci. 9 (2004) 77e81.

529 [27] F. Ianni, Z. Pataj, H. Gross, R. Sardella, B. Natalini, W. Lindner, M. L€ammerhofer, Direct  
530 enantioseparation of underivatized aliphatic 3-hydroxyalkanoic acids with a quinine-based zwitterionic  
531 chiral stationary phase, J. Chromatogr. A 1363 (2014) 101e108.

532 [28] V. Mimini, F. Ianni, F. Marini, H. Hettegger, R. Sardella, W. Lindner, Electrostatic attraction-repulsion  
533 model with Cinchona alkaloid-based zwitterionic chiral stationary phases exemplified for zwitterionic  
534 analytes, Anal. Chim. Acta 1078 (2019) 212e220.

535 [29] I. Ilisz, A. Bajtai, A. P eter, W. Lindner, Cinchona Alkaloid-Based Zwitterionic chiral stationary phases  
536 applied for liquid chromatographic enantiomer separations: an overview, Methods Mol. Biol. 1985 (2019)  
537 251e277.

538 [30] R. Sardella, A. Carotti, G. Manfroni, D. Tedesco, A. Martelli, C. Bertucci, V. Cecchetti, B. Natalini,  
539 Enantioresolution, stereochemical characterization and biological activity of a chiral large-conductance  
540 calcium-activated potassium channel opener, J. Chromatogr. A 1363 (2014) 162e168.

541 [31] B. Cerra, A. Carotti, D. Passer, R. Sardella, G. Moroni, A. Di Michele, A. Macchiarulo, R. Pellicciari, A.  
542 Gioiello, Exploiting chemical toolboxes for the expedited generation of tetracyclic quinolines as a novel class  
543 of PXR agonists, ACS Med. Chem. Lett. 10 (2019) 677e681.

544 [32] L. Mercolini, M. Protti, Biosampling strategies for emerging drugs of abuse: towards the future of  
545 toxicological and forensic analysis, J. Pharmaceut. Biomed. Anal. 130 (2016) 202e219.

546 [33] L. Mercolini, M.A. Saracino, M. Protti, Current advances in biosampling for therapeutic drug monitoring  
547 of psychiatric CNS drugs, Bioanalysis 7 (2015) 1925e1942.

548 [34] A.C. Evans, A.S. Petit, S.G. Guillen, A.J. Neukirch, S. V Hoffmann, N.C. Jones, Chiroptical characterization  
549 tools for asymmetric small molecules - experimental and computational approaches for electronic circular  
550 dichroism (ECD) and anisotropy spectroscopy, RSC Adv. 11 (2021) 1635e1643.

551 [35] P.J. Stephens, F.J. Devlin, C.F. Chabalowski, M.J. Frisch, Ab-initio calculation of vibrational absorption  
552 and circular-dichroism spectra using densityfunctional force-fields, J. Phys. Chem. 98 (1994) 11623e11627.

553 [36] J.D. Chai, M. Head-Gordon, Long-range corrected hybrid density functionals with damped atomeatom  
554 dispersion corrections, Phys. Chem. Chem. Phys. 10 (2008) 6615e6620.

555 [37] A.E. Hansen, K.L. Bak, Ab initio calculations and display of enantiomeric and nonenantiomeric

556 anisotropic circular Dichroism: the lowest  $p / p^*$  excitation in butadiene, cyclohexadiene, and methyl-  
557 substituted cyclohexadiene, *J. Phys. Chem. A* 104 (2000) 11362e11370.

558 [38] J. Autschbach, T. Ziegler, S.J.A. Van Gisbergen, E.J. Baerends, Chiroptical properties from time-  
559 dependent density functional theory. I. Circular dichroism spectra of organic molecules, *J. Chem. Phys.* 116  
560 (2002) 6930e6940.

561 [39] C. Bannwarth, S. Grimme, A simplified time-dependent density functional theory approach for  
562 electronic ultraviolet and circular dichroism spectra of very large molecules, *Comput. Theor. Chem.* 1040  
563 (2014) 45e53.

564 [40] F. Neese, The ORCA program system, *Wires Comput. Mol. Sci.* 2 (2012) 73e78. [41] P.J. Stephens, N.  
565 Harada, ECD cotton effect approximated by the Gaussian curve and other methods, *Chirality* 22 (2010)  
566 229e233.

567 [42] T. Bruhn, A. Schaumloffel, Y. Hemberger, G. Bringmann, SpecDis: quantifying the Comparison of  
568 calculated and experimental electronic circular dichroism spectra, *Chirality* 25 (2013) 243e249.

569 [43] R. Sardella, A. Macchiarulo, F. Urbinati, F. Ianni, A. Carotti, M. Kohout, W. Lindner, A. Peter, I. Ilisz,  
570 Exploring the enantio recognition mechanism of Cinchona alkaloid-based zwitterionic chiral stationary  
571 phases and the basic trans-paroxetine enantiomers, *J. Separ. Sci.* 41 (2018) 1199e1207.

572 [44] W.G. Hoover, Canonical dynamics: equilibrium phase-space distributions, *Phys. Rev. A* 31 (1985)  
573 1695e1697.

574 [45] S. Nos e, A unified formulation of the constant temperature molecular dynamics methods, *J. Chem.*  
575 *Phys.* 81 (1984) 511e519.

576 [46] D.E. Shaw, A fast, scalable method for the parallel evaluation of distancelimited pairwise particle  
577 interactions, *J. Comput. Chem.* 26 (2005) 1318e1328.

578 [47] A. Carotti, F. Ianni, S. Sabatini, A. Di Michele, R. Sardella, G.W. Kaatz, W. Lindner, V. Cecchetti, B.  
579 Natalini, The "racemic approach" in the evaluation of the enantiomeric NorA efflux pump inhibition activity  
580 of 2-phenylquinoline derivatives, *J. Pharmaceut. Biomed. Anal.* 129 (2016) 164e173.

581 [48] N. Greco, M. Kohout, A. Carotti, R. Sardella, B. Natalini, F. Fülöp, W. Lindner, A. Peter, I. Ilisz,  
582 Mechanistic considerations of enantio recognition on novel Cinchona alkaloid-based zwitterionic chiral  
583 stationary phases from the aspect of the separation of trans-paroxetine enantiomers as model compounds,  
584 *J. Pharmaceut. Biomed. Anal.* 124 (2016) 164e173.

585 [49] C.V. Hoffmann, R. Pell, M. L€ammerhofer, W. Lindner, Synergistic effects on enantioselectivity of  
586 zwitterionic chiral stationary phases for separations of chiral acids, bases, and amino acids by HPLC, *Anal.*  
587 *Chem.* 80 (2008) 8780e8789.

588 [50] F. Ianni, A. Carotti, M. Marinozzi, G. Marcelli, A. Di Michele, R. Sardella, W. Lindner, B. Natalini,



589 Diastereo- and enantioseparation of a Na-Boc amino acid with a zwitterionic quinine-based stationary  
590 phase: focus on the stereo recognition mechanism, *Anal. Chim. Acta* 885 (2015) 174e182.

591 [51] I. Ilisz, N. Grecs o, A. Aranyi, P. Suchotin, D. Tymecka, B. Wilenska, A. Misicka, F. Fülöp, W. Lindner, A.  
592 P eter, Enantioseparation of b2-amino acids on cinchona alkaloid-based zwitterionic chiral stationary  
593 phases. Structural and temperature effects, *J. Chromatogr. A* 1334 (2014) 44e54.

594 [52] C. Calder on, J. Horak, M. L€ammerhofer, Chiral separation of 2-hydroxyglutaric acid on cinchonan  
595 carbamate based weak chiral anion exchangers by highperformance liquid chromatography, *J. Chromatogr.*  
596 *A* 1467 (2016) 239e245.

597 [53] C. Calder on, M. L€ammerhofer, Chiral separation of short chain aliphatic hydroxycarboxylic acids on  
598 cinchonan carbamate-based weak chiral anion exchangers and zwitterionic chiral ion exchangers, *J.*  
599 *Chromatogr. A* 1487 (2017) 194e200.

600 [54] A. Bajtai, I. Ilisz, A. P eter, W. Lindner, Liquid chromatographic resolution of natural and racemic  
601 Cinchona alkaloid analogues using strong cation- and zwitterion ion-exchange type stationary phases.  
602 Qualitative evaluation of stationary phase characteristics and mobile phase effects on stereoselectivity and  
603 retention, *J. Chromatogr. A* 1609 (2020) 460498.

604 [55] C.V. Hoffmann, R. Reischl, N.M. Maier, M. L€ammerhofer, W. Lindner, Stationary phase-related  
605 investigations of quinine-based zwitterionic chiral stationary phases operated in anion-, cation-, and  
606 zwitterion-exchange modes, *J. Chromatogr. A* 1216 (2009) 1147e1156.

607 [56] I. Ilisz, A. Bajtai, W. Lindner, A. P eter, Liquid chromatographic enantiomer separations applying chiral  
608 ion-exchangers based on Cinchona alkaloids, *J. Pharmaceut. Biomed. Anal.* 159 (2018) 127e152.

609 [57] G. Lajk o, N. Grecs o, G. T oth, F. Fülöp, W. Lindner, I. Ilisz, A. P eter, Liquid and subcritical fluid  
610 chromatographic enantioseparation of Na-Fmoc proteinogenic amino acids on Quinidine-based zwitterionic  
611 and anion-exchanger type chiral stationary phases. A comparative study, *Chirality* 29 (2017) 225e238.

612 [58] I. Ilisz, N. Grecs o, A. Misicka, D. Tymecka, L. L az ar, W. Lindner, A. P eter, Comparison of the  
613 separation performances of cinchona alkaloid-based zwitterionic stationary phases in the  
614 enantioseparation of b2- and b3-amino acids, *Molecules* 20 (2015) 70e87.

615 [59] D. Tan acs, T. Orosz, I. Ilisz, A. P eter, W. Lindner, Unexpected effects of mobile phase solvents and  
616 additives on retention and resolution of N-Acyl-D,LLeucine applying cinchonane-based chiral ion  
617 exchangers, *J. Chromatogr. A* 1648 (2021) 462212.

618 [60] R. Pell, S. Si c, W. Lindner, Mechanistic investigations of cinchona alkaloidbased zwitterionic chiral  
619 stationary phases, *J. Chromatogr. A* 1269 (2012) 287e296.

620 [61] F. Ianni, R. Sardella, A. Carotti, B. Natalini, W. Lindner, M. L€ammerhofer, Quinine-based zwitterionic  
621 chiral stationary phase as a complementary tool for peptide analysis: mobile phase effects on enantio- and

622 stereoselectivity of underivatized oligopeptides, *Chirality* 28 (2016) 5e16.

623 [62] L.O. Zamir, R. Tiberi, K.A. Devor, F. Sauriol, S. Ahmad, R.A. Jensen, Structure of D-prephenyllactate a  
624 carboxycyclohexadienyl metabolite from *neurospora crassa*, *J. Biol. Chem.* 33 (1988) 17284e17290.

625 [63] American Conference of Governmental Industrial Hygienists, Threshold Limit Values for Chemical  
626 Substances and Physical Agents and Biological Indices, American Conference of Governmental Industrial  
627 Hygienists, Cincinnati, 1991.

628 [64] A.R. Choi, S.G. Im, M.Y. Lee, S.H. Lee, Evaluation of the suitability of establishing biological exposure  
629 indices of styrene, *Safe. Health. Work* 10 (2019) 103e108.

630 [65] European Medicines Agency (EMA), Committee for Medicinal Products for Human Use (CHMP),  
631 Guideline on Bioanalytical Method Validation, EMEA/ CHMP/EWP/192217/2009, London, UK, 2011.

632

## Supplementary Material

### Efficient enantioresolution of aromatic $\alpha$ -hydroxy acids with *Cinchona* alkaloid-based zwitterionic stationary phases and volatile polar-ionic eluents

Ina Varfaj<sup>1a</sup>, Michele Protti<sup>2a</sup>, Alessandro Di Michele<sup>3</sup>, Alceo Macchioni<sup>4</sup>, Wolfgang Lindner<sup>5</sup>,

Andrea Carotti<sup>1\*</sup>, Roccaldo Sardella<sup>1,6\*</sup>, Laura Mercolini<sup>2</sup>

<sup>1</sup>*Department of Pharmaceutical Sciences, University of Perugia, Via Fabretti 48, 06123 - Perugia, Italy.*

<sup>2</sup>*Department of Pharmacy and Biotechnology (FaBiT), Alma Mater Studiorum, University of Bologna, Via Belmeloro 6, 40126 - Bologna, Italy.*

<sup>3</sup>*Department of Physics and Geology, University of Perugia, Via Pascoli 1, 06123 - Perugia, Italy*

<sup>4</sup>*Department of Chemistry, Biology and Biotechnology, University of Perugia, Via Elce di Sotto 8, 06123 - Perugia, Italy.*

<sup>5</sup>*Department of Analytical Chemistry, University of Vienna, Währinger Strasse 38, 1090 - Vienna, Austria.*

<sup>6</sup>*Center for Perinatal and Reproductive Medicine, University of Perugia, Santa Maria della Misericordia University Hospital, 06132 Perugia, Italy.*

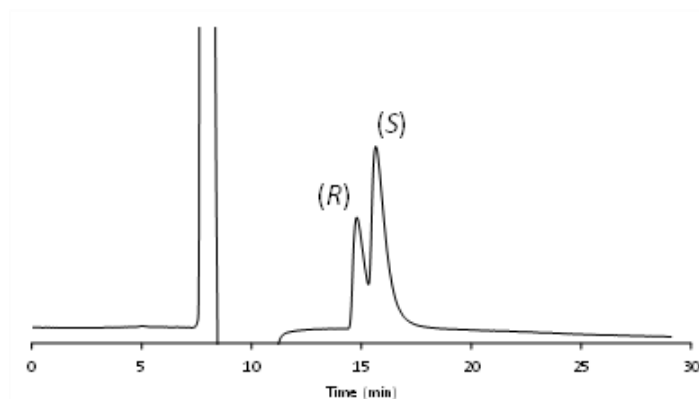
<sup>a</sup> Ina Varfaj and Michele Protti contributed equally to this work.

\*Corresponding authors:

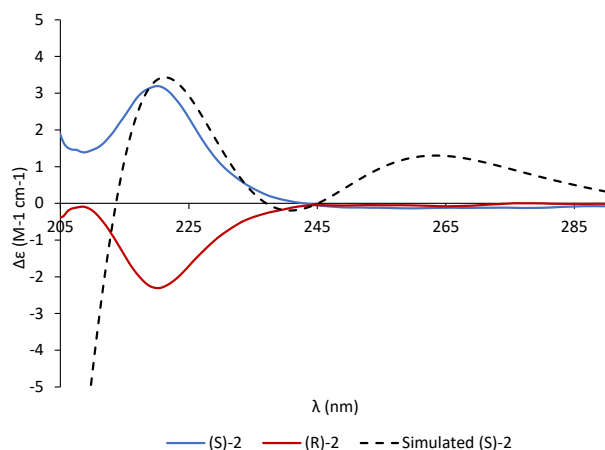
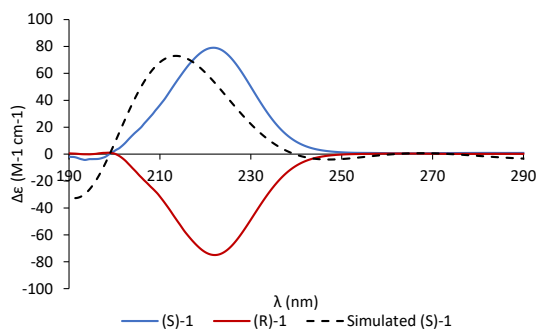
Andrea Carotti, email: andrea.carotti@unipg.it

Roccaldo Sardella, email: roccaldo.sardella@unipg.it

**Figure 1S.** Chromatograms of compound 2 obtained with CSP 2 [CHIRALPAK® ZWIX(+), from Chiral Technology Europe - Strasbourg, France) under the optimal [ACN/MeOH 95/5 (v/v) with 80 mM FA] mobile phase composition and experimental conditions: eluent flow rate, 0.2 mL/min; column temperature, 25 °C; detection wavelength, 254 nm.



**Figure 2S.** Experimental ECD spectra of the first- (blue line) and second-eluted (red line) enantiomeric fraction of (A) compound 1 and (B) compound 2. The theoretical spectrum of the (S)-enantiomer is reported as black dashed-line.



**Figure 3S.** ESI-UHPLC-MS chromatogram obtained from the analysis of a DUS sample spiked with *rac-1* (on-spot concentration: 100 ng/mL). Extracted ion:  $m/z$  151.17.

