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1 **Impact of ironing on indoor particle levels and composition**

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13 **Abstract**

14 Domestic chores are an important part of the household's daily routine and can contribute
15 significantly to personal exposure. In this study, the particulate mass and number
16 concentrations were assessed when using two irons (steam iron and steam iron with
17 boiler) under distinct conditions (minimum ventilation and indoor doors open). The
18 detailed PM₁₀ chemical characterisation included organic and elemental carbon, elements
19 and organic speciation. Particle number emission rates ranged from $8.1 \pm 0.09 \times 10^{11}$ to
20 $15 \pm 3.4 \times 10^{11}$ particles min⁻¹. Ratios of peak to background levels indicate that ironing
21 can elevate the ultrafine particle number concentrations by a factor ranging from 35 to
22 194. PM₁₀ emission rates from steam iron, under minimum ventilation conditions ($6.6 \pm$
23 $1.4 \mu\text{g s}^{-1}$), were higher than those from steam iron with the doors open ($1.9 \pm 1.6 \mu\text{g s}^{-1}$).
24 The highest particle number and mass emission rates were recorded when the steam iron
25 with boiler was used. Regarding the chemical composition of particles, elemental carbon
26 and strontium were only detected during ironing. Bromide concentrations increased
27 noticeably over background levels (9 to 51 times) during ironing. PM₁₀ samples
28 encompassed a wide range of organic compounds, part of which can be attributed to the
29 handling of textiles and the use of detergents, fabric softeners, cosmetics and personal
30 care products. Substances emitted by volatilisation or shedding of textile fibres, or due to
31 handling, can contribute to human exposure through inhalation. The cancer risks
32 associated with inhalation of metals and PAH were found to be negligible.

34 **Keywords:** Indoor air quality, Ironing, Particulate matter, Elemental composition,
35 OC/EC, Organic compounds.

37 **1. Introduction**

38 Every year, ambient air pollution causes millions of premature deaths globally [1].
39 Particulate matter (PM), classified by the International Agency for Research on Cancer
40 (IARC) as carcinogenic for humans (Group 1) [2], induces adverse health effects,
41 including respiratory symptoms, exacerbation of chronic respiratory and cardiovascular
42 diseases and decreased lung function [3,4,5,6]. Indoor exposure to PM is likely to be an
43 important contributor to the adverse health effects since most people spend nearly 90%
44 of their time in enclosed environments, especially in residential settings [7,8,9], meaning
45 that much of the exposure to aerosols through inhalation occurs in built environments
46 [10,11]. Indoor particulate matter includes particles that infiltrate from outdoors, particles
47 from indoor sources and particles generated by indoor air chemistry [12,13,14,15].

48 A substantial body of evidence shows that several household activities, such as cooking
49 [16,17], use of biomass burning stoves for heating [18,19,20,21,22,23,24,25] and tobacco
50 smoking [26,27,28,29,30,31], are significant sources of particulate matter (mass and
51 number). Additionally, other indoor sources such as vacuuming [30,32,33,34,35,36,37,
52 38], use of air fresheners [30,39,40], burning candles [31,37,40,41] and ironing [30,
53 31,42,43,44] were also investigated. Furthermore, the physicochemical characteristics of
54 some sources of indoor PM, such as cooking [17], cigarette smoking [45], incense burning
55 [46] and use of combustion appliances for heating purposes [47] have been characterised.
56 The interest in the PM chemical composition is driven by the risk associated with specific
57 PM components (e.g. PAHs, heavy metals, etc.) and also by the possibility of using
58 certain compounds as tracers for source apportionment in indoor environments [12, 48].
59 Despite the significant data provided by the above-mentioned studies, few researches,
60 however, have focused on the characterisation of particles from other indoor sources.

61 In the European Union, it is estimated that there are more than 300 million electric irons
62 in use with a sale of about 40 million units per year [49]. In the market, there are several
63 iron brands offering diverse solutions, such as dry irons (nowadays sparsely in-use),
64 steam irons, travel irons and steam irons with boiler (steam stations), each with their own
65 features concerning power, flow of steam, sole plate, safety mechanisms and temperature
66 adjustment [50]. Ironing is one of the most time-consuming processes of laundry
67 treatment [51]. Regarding this household task, only particle mass [43] and number
68 [30,31,42,44] have been assessed so far. Taking into account that identification and
69 characterisation of indoor emission sources is crucial to develop an effective exposure

70 control, the aim of the present study is to assess the impact of ironing on particulate matter
71 mass and number concentrations in indoor air. The detailed chemical characterisation of
72 particulate matter was obtained in order to perform a health risk assessment (carcinogenic
73 and noncarcinogenic) from the inhalation of PM₁₀ and to identify compounds that may be
74 used as specific source tracers in future work.

75

76 **2. Materials and methods**

77 **2.1. Sampling sites and strategy**

78 Considering that the use of steam during ironing provides a fast effective method to
79 transmit significant heat to the fabric and remove creases [52], two different types of
80 steam irons (steam iron and a steam iron with boiler) were selected to carry out the
81 measurements in the present study. The set of items that were ironed represented
82 approximately the clothes accumulated over a week by a family of 4 people. The clothes
83 comprised pieces of varied composition (e.g. cotton, polyester, etc.) and included freshly
84 washed linen (tablecloths, bedsheets and towels) and daily garment, such as shirts, t-
85 shirts, sweatshirts, blouses, jeans and trousers. The measurements were performed in the
86 living room (volume = 91.9 m³) of a suburban Spanish house (León) under minimum
87 ventilation conditions with both the ironing systems (all the room doors and windows
88 were kept closed - condition I). Additionally, the particulate levels generated during
89 ironing with the steam iron were also characterised while keeping the living room door
90 opened and the windows closed (condition II). On average, measurements were
91 conducted for three and a half hours and each test condition was repeated twice in
92 different weeks. During the execution of the task, no other activities took place in the
93 house. However, daily life activities were conducted before the activity started since the
94 house was occupied. After ceasing the activity, sampling continued until the particle
95 concentration decreased to levels of the same order as the ones recorded before the
96 activation of the source. Background indoor air measurements were also performed, in
97 the absence of indoor activities, during a weekend when the homeowners were away.
98 Background levels were monitored for periods of time similar to those recorded during
99 sampling with ironing.

100 An air quality probe (model 7545, TSI) was used to monitor continuously the temperature,
101 relative humidity and CO₂ (1-min resolution). Ventilation rates were estimated by the
102 CO₂ concentration decay method as described by Alves et al. [53].

103 A real-time laser photometric instrument (DustTrak DRX 8533, TSI) was used to record
104 particulate matter mass concentrations over time (PM_1 , $PM_{2.5}$ and PM_{10} , 1-min
105 resolution). Particle number concentrations and size distribution from 8 to 322 nm were
106 measured with a scanning mobility particle sizer (SMPS; Classifier model 3071, CPC
107 model 3022, TSI Incorporated).

108 PM_{10} sampling for gravimetric and chemical analysis was carried out from the activation
109 of the source until the iron was switched off (about 3.5 h) using simultaneously a high-
110 volume sampler (MCV, model CAV-A/mb) operated at $30\text{ m}^3\text{ h}^{-1}$ and a low volume
111 sampler (TCR TECORA, model 2.004.01) at a flow of $2.3\text{ m}^3\text{ h}^{-1}$. The first sampling
112 instrument was equipped with pre-weighed quartz fibre filters (150 mm diameter,
113 Pallflex®) while the second collected the samples on Teflon membrane filters (47 mm
114 diameter, Pall Corporation). The collected mass of particles on filters was gravimetrically
115 determined at an accuracy of 0.01 mg (XPE105 DeltaRange®, Mettler Toledo). The inlet
116 of the samplers was placed at the breathing zone and in close proximity to the iron board.
117 The comparison of PM_{10} concentrations obtained from the simultaneous measurements
118 with MCV and Tecora presented a strong linear correlation ($r^2 = 0.96$) with a slope close
119 to the unity (0.94). The comparison between the PM_{10} concentrations determined with the
120 gravimetric and photometric instruments also displayed strong correlations coefficients
121 ($r^2 = 0.92$ and $r^2 = 0.96$ with the MCV and Tecora, respectively).

122

123 **2.2. Analytical techniques**

124 The organic (OC) and elemental (EC) carbonaceous content in the PM_{10} samples (quartz
125 filters) was analysed by a thermal optical transmission technique described in detail in
126 previous studies [54]. For mass balance purposes, OC was converted into organic matter
127 (OM) to account for oxygen, nitrogen, hydrogen and other atoms not determined by the
128 thermo-optical method. The multiplier factor adopted was 1.9 taking into account the
129 presence of highly oxygenated compounds determined by gas chromatograph-mass
130 spectrometer (GC-MS) [55].

131 Concentrations of elements with $Z > 10$ were measured in the PM_{10} samples (Teflon
132 filters) by proton-induced X-ray analysis (PIXE, proton beam energy 3 MeV) at the
133 INFN-LABEC laboratory [56]. A detailed description of the method can be found
134 elsewhere [57]. For mass balance purposes, the measured element concentrations were
135 converted into the respective mass concentrations of the most common oxides (SiO_2 ,
136 Al_2O_3 , MgO , MnO , Fe_2O_3 , TiO_2 , K_2O , etc.).

137 To characterise the organic fraction, portions of the quartz filters were extracted first by
 138 refluxing dichloromethane for 24 h and then for 10 min intervals with methanol (three
 139 times) using an ultrasonic bath. The extracts were filtered, concentrated and then
 140 evaporated to dryness under high pure nitrogen gas. The total organic extracts were
 141 fractionated by flash chromatography and analysed by GC–MS. A detailed description of
 142 the method and equipment can be found elsewhere [58]. The organic compounds were
 143 identified by comparing the spectra of the samples with those in the Wiley mass spectral
 144 reference libraries. Further confirmation was carried out with authentic standards.
 145 Field blanks were prepared, handled and analysed by the same procedures as the samples
 146 and the data was subtracted to obtain corrected results.

147

148 **2.3. Estimation of particulate emission rates**

149 The calculation of emission rates was carried out based on the mass-balance equation
 150 [21,36,59]. The rate of change in indoor aerosol concentrations with respect to time is
 151 expressed as follows (equation (1)):

$$152 \quad \frac{dC_{in}}{dt} = P\alpha C_{out} + \frac{Q_s}{V} - (\alpha + \kappa)C_{in} \quad (1)$$

153 where C_{in} and C_{out} are the indoor and outdoor particle concentrations, respectively, P is
 154 the penetration efficiency, κ is the deposition rate, α is the air exchange rate, Q_s is the
 155 indoor particle generation rate, t is time and V is the room volume.

156 The average emission rates were calculated assuming a penetration efficiency equal to
 157 one, well-mixed conditions and using average values instead of functions (equation (2)).
 158 Additional assumptions about the experimental conditions were made as described by He
 159 et al. [60].

$$160 \quad \overline{Q_s} = V \times \left[\frac{C_{in} - C_{in0}}{\Delta t} + \overline{(\alpha + \kappa)} \overline{C_{in}} - \alpha C_{in0} \right] \quad (2)$$

161 In equation (2), $\overline{Q_s}$ is the average particle emission rate (mass and number), C_{in} and C_{in0}
 162 are the peak and initial indoor particle concentrations (mass and number), respectively,
 163 Δt is the time difference between the initial and peak particle concentration, $\overline{(\alpha + \kappa)}$ is
 164 the average removal rate and α is the average air exchange rate. This equation ignores the
 165 aerosol dynamic processes such as condensation, evaporation and coagulation that
 166 contribute to formation and removal of particles [36].

167 The average removal rate was determined as described in previous studies [61, 62, 63,
168 64]. Briefly, assuming that when an indoor source is active the contribution of outdoor
169 penetration to indoor concentrations is negligible, the decay of particles indoors after the
170 source stopped is described by equation (3):

$$171 \quad \frac{dC_{in}}{dt} = -(\alpha + \kappa)C_{in} \quad (3)$$

172 Integrating equation (3), the following expression is obtained (equation (4)):

$$173 \quad \ln\left(\frac{C_{in_t}}{C_{in_0}}\right) = -(\alpha + \kappa)t \quad (4)$$

174 The slope obtained from the plot of $\ln(C_{in}/C_{in_0})$ versus time is equal to $-(\alpha + \kappa)$ [61, 62,
175 63, 64].

176

177 **2.4. Enrichment factors**

178 Enrichment factors (EFRs) were calculated to determine whether the indoor PM
179 originated from crustal or non-crustal sources following equation (5):

$$180 \quad EFR = \frac{(E/R)_{air}}{(E/R)_{crust}} \quad (5)$$

181 where E is the concentration of the element under analysis and R is the concentration of
182 the reference element. Silicon was used in this study as a reference because it is a major
183 constituent of the earth's crust. The average element concentrations in soil were obtained
184 from Wedepohl [65].

185

186 **2.5. Health risk assessment**

187 In this study, a health risk analysis for estimating the occurrence of adverse health effects
188 resulting from the inhalation of PM₁₀ was performed by using inorganic elements and
189 polycyclic aromatic hydrocarbon (PAH) concentrations.

190 The reference concentration (R_fC, ng m⁻³) was used for toxic elements, while the
191 inhalation unit risk (IUR, ng m⁻³) was adopted for carcinogenic compounds (As, Cr (VI),
192 Pb, Co, Cd, Ni and benzo[a]pyrene). These values were taken from databases provided
193 by USEPA [66,67]. In the case of unavailability of reference concentrations, reference
194 doses for oral exposure (R_fD) were used to derive R_fC values as described by USEPA
195 [68]. Regarding chromium, the total concentration was determined in this study. Taking
196 into account that it was established that the concentration ratio of Cr(VI) to Cr(III) in the

197 air is about 1 to 6 [68], the excess cancer risk of Cr(VI) was calculated as one seventh of
198 total Cr concentration.

199 The exposure concentration (EC_x) of the selected non-carcinogenic elements and
200 carcinogenic elements was calculated as follows [69]:

$$201 \quad EC_x = (CA \times ET \times EF \times ED) / AT \quad (6)$$

202 where EC_x is the exposure concentration (ng m^{-3}), CA is the compound concentration
203 (ng m^{-3}), ET is the exposure time, EF is the exposure frequency, ED is the exposure
204 duration and AT is the averaging time. The exposure time used in the calculations was
205 based on the results of a survey on consumer behaviour regarding laundry treatment in
206 Germany [51]. Taking into account the survey results, the exposure concentration was
207 calculated assuming an ironing frequency of once a week for 2 h over 70 years of activity
208 in housekeeping during human life; therefore, these values were assumed for ET, EF, ED
209 and AT, respectively: 2 h d^{-1} , 48 d y^{-1} , 70 y, $70 \text{ y} \times 365 \text{ d y}^{-1} \times 24 \text{ h d}^{-1}$.

210 The cancer risk from inhalation exposure to PAHs was estimated using the
211 benzo[a]pyrene equivalent concentrations (BaP_{eq} , ng m^{-3}) as CA. The BaP_{eq}
212 concentrations were calculated multiplying the particle-phase concentrations of PAHs
213 (EPA 16 priority PAHs) by the respective toxic equivalent factors (TEF), which were
214 taken from Bari et al. [70].

215 For non-carcinogenic elements, the hazard quotient (HQ) was calculated as follows [69]:

$$216 \quad HQ = EC / R_fC \quad (7)$$

217 The excess cancer risk associated with the carcinogenic elements was calculated as
218 follows [69]:

$$219 \quad \text{Risk} = IUR \times EC \quad (8)$$

220

221 **3. Results**

222 **3.1. Comfort parameters**

223 The mean temperature and relative humidity ranged between 21.8 and 25.7 °C and
224 between 40.5 and 60.6%, respectively, for the whole set of measurements (Table 1). The
225 increase in the relative humidity over background levels (before the activation of the
226 source) was, on average, from 12 to 14% and from 13 to 17% during steam iron and steam
227 iron with boiler (condition I), respectively. When the door of the living room was closed,
228 condition I (steam iron and steam iron with boiler), the ventilation rate varied between

229 0.16 and 0.42 h⁻¹. During condition II, when the door of the living room was open, the
 230 average ventilation rate was 1.8 ± 0.39 h⁻¹.

231 Table 1. Sampling conditions, PM₁₀ mass and particle number concentrations and
 232 emission rates during ironing.

	Steam iron I	Steam iron II	Steam iron with boiler
N	2	2	2
Air exchange rate (α , h ⁻¹)	0.25 ± 0.13	1.8 ± 0.39	0.38 ± 0.06
PM ₁₀ initial mass concentration ($\mu\text{g m}^{-3}$)	51 ± 2.8	16 ± 1.4	21 ± 2.8
PM ₁₀ peak mass concentration ($\mu\text{g m}^{-3}$)	340 ± 62	98 ± 16	444 ± 16
PM _{2.5} /PM ₁₀ (%)	94 ± 0.2	87 ± 5.7	94 ± 2.3
PM ₁ /PM ₁₀ (%)	93 ± 0.4	85 ± 6.3	93 ± 2.6
Particle number initial concentration (particles × 10 ³ cm ⁻³)	3.6 ± 1.3	6.0 ± 1.6	7.2 ± 3.4
Particle peak number concentration (particles × 10 ⁵ cm ⁻³)	4.4 ± 1.2	2.6 ± 0.03	3.6 ± 0.30
Emission rate PM ₁₀ ($\mu\text{g s}^{-1}$)	6.6 ± 1.4	1.9 ± 1.6	8.3 ± 3.1
Emission rate particle number (particles × 10 ¹¹ min ⁻¹)	12 ± 2.3	8.1 ± 0.09	15 ± 3.5

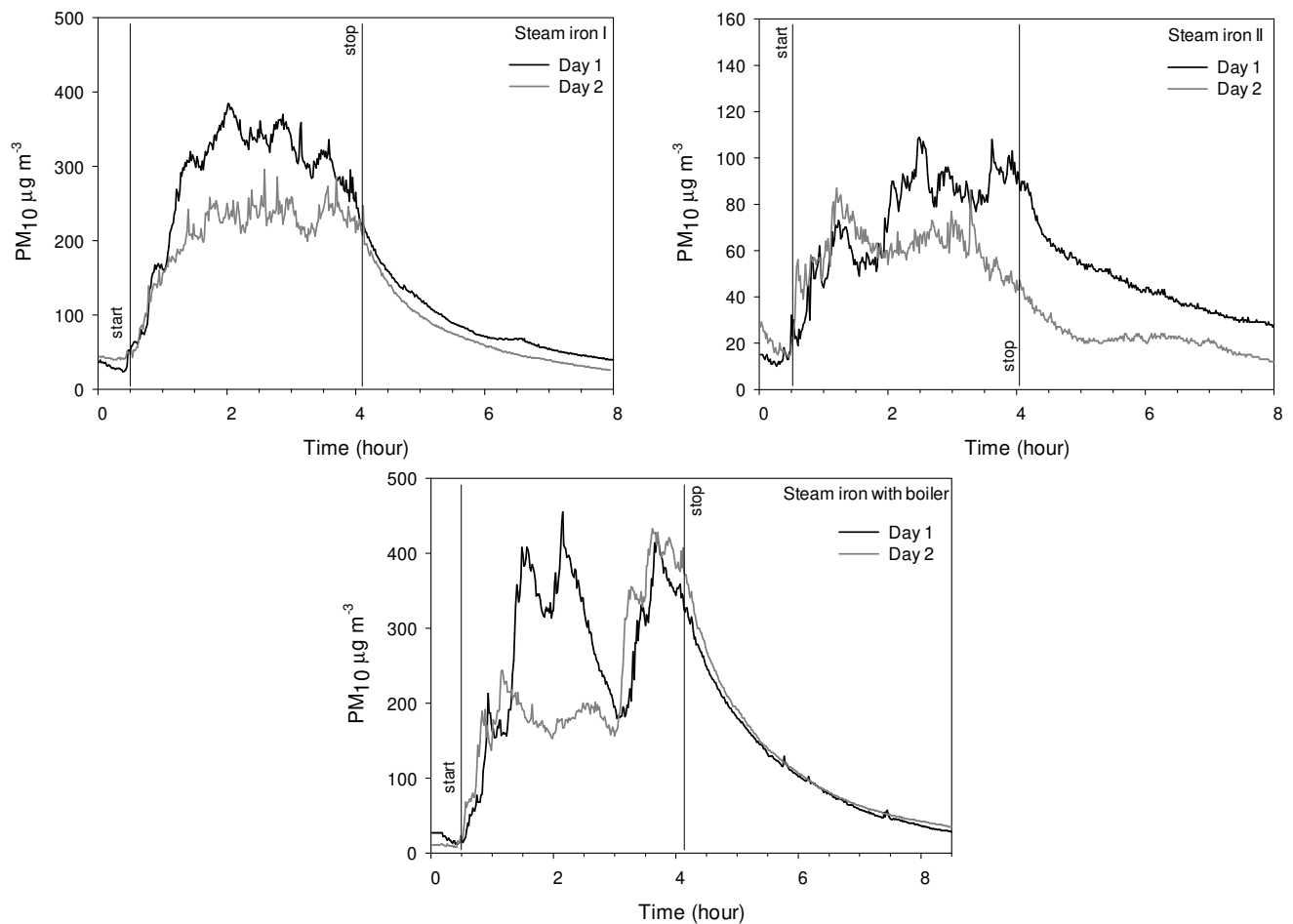
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234 3.2. Particulate matter

235 3.2.1. Mass concentrations

236 Fig. 1 shows the time resolved PM₁₀ mass concentrations during ironing. On average,
 237 increases over PM₁₀ initial concentrations (before the activation of the source) of 4.8, 4.2,
 238 12 times were observed when the steam iron (condition I), steam iron (condition II) and
 239 steam ironing with boiler (condition I) were in use, respectively. The PM₁₀ mass
 240 concentration profiles during steam iron (condition I) were similar on both measurement
 241 days, although the values were generally lower on the second day of experiments. During
 242 the first hour and a half using the steam iron (condition II), slightly higher PM₁₀
 243 concentrations were recorded on the second day of measurements, while the opposite,
 244 with more marked differences in the PM₁₀ levels, was recorded for the remaining period
 245 of activity. For the steam iron with boiler, during the first two and a half hours,
 246 concentrations were much higher on the first day of measurements in comparison with
 247 those recorded on the second day, while in the last hour the profiles and concentrations
 248 were similar. The discrepancies observed, both for levels and profiles, may result from
 249 differences in the number, size and composition of ironed garments. Peak mass
 250 concentrations ranging from 87 $\mu\text{g m}^{-3}$ (steam iron II) to 455 $\mu\text{g m}^{-3}$ (steam iron with
 251 boiler) were recorded. Steam ironing in an enclosed space (condition I) generated peak
 252 concentrations three to four times higher than those observed with the room door open
 253 (condition II). Higher peak concentrations during steam ironing with boiler can result

254 from the generation of steam at high pressure, which likely enhances the shedding of
 255 fibres from clothing and consequently the mass of particles generated in comparison with
 256 the conventional steam iron. Lower PM₁₀ peak concentrations were recorded by Schiavon
 257 et al. [43], ranging from 86.9 to 119.8 µg m⁻³, during ironing (steam iron with boiler) in
 258 a closed and poorly ventilated room. In addition of being released during ironing, particles
 259 can also be emitted from other actions that are closely connected to the studied activity
 260 such as handling clothes before and after ironing. In fact, previous studies reported that
 261 manipulation of clothing can be a strong source of indoor aerosol particles [71,72].



262
 263 Fig. 1. PM₁₀ mass concentrations during ironing.

264
 265 During the manipulation of a cotton shirt, Licina et al. [71] reported sharp PM₁₀
 266 concentration peaks in the breathing zone, at times exceeding 40 µg m⁻³. Ferro et al. [72]
 267 also reported that folding clothes (mean PM₁₀ personal exposure from 15-min over 250
 268 µg m⁻³) and blankets (mean PM₁₀ personal exposure from 15-min over 200 µg m⁻³)
 269 resulted in high PM exposure.

270 In the present study, PM₁₀ concentrations decreased to background levels (concentration
271 in the room before the activity started) about 3 (steam iron I and II) to 5 h (steam iron
272 with boiler) after turning off the iron. Schiavon et al. [43] observed that one hour after
273 ceasing ironing the concentrations were still three times higher than the ones recorded
274 before switching the iron on.

275 Fine particles dominated the PM₁₀ mass as indicated by PM_{2.5}/PM₁₀ and PM₁/PM₁₀
276 average ratios ranging from 85 to 94% (Table 1). Contrarily to the results obtained here,
277 Schiavon et al. [43] reported PM_{2.5}/PM₁₀ and PM₁/PM₁₀ ranging from 28 to 56% and from
278 19 to 46%, respectively.

279 The estimated PM₁₀ emission rates from steam iron under minimum ventilation
280 (condition I) were, on average, over three times higher ($6.6 \pm 1.4 \mu\text{g s}^{-1}$) than those from
281 steam iron with the living room door open (condition II) ($1.9 \pm 1.6 \mu\text{g s}^{-1}$). The highest
282 emission rates were recorded when using the steam iron with boiler ($8.3 \pm 3.1 \mu\text{g s}^{-1}$)
283 (Table 1).

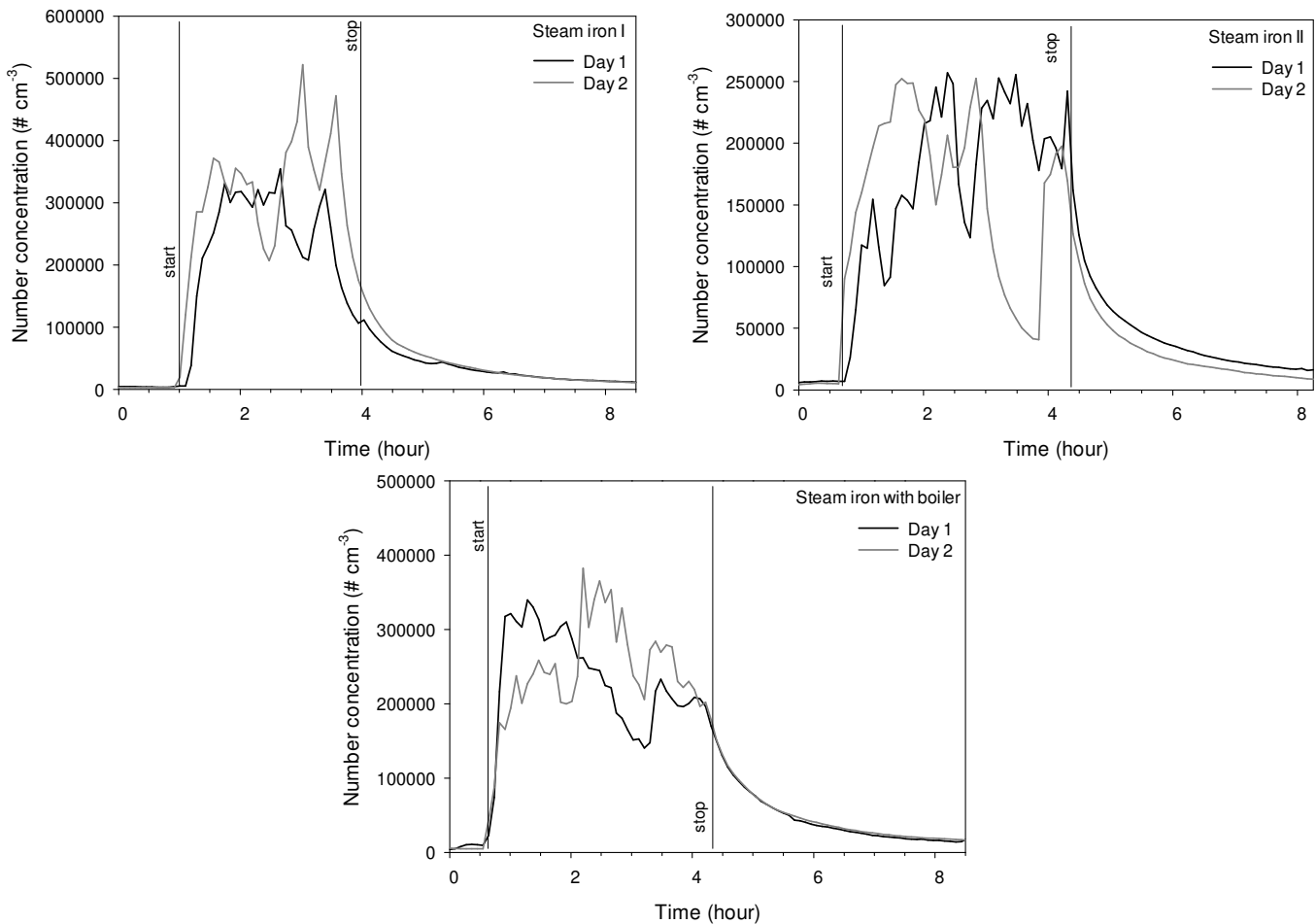
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285 **3.2.2. Number concentrations**

286 Fig. 2 illustrates the time evolution of the total particle number concentration during
287 ironing. As observed for PM₁₀ mass concentrations, differences in the levels and profiles
288 of number concentrations were also recorded. When ironing started, the number
289 concentration of particles increased sharply. Although a rapid increase was observed
290 when the activity started, it took about 1–2 h to reach peak concentrations depending on
291 the iron and condition tested. When the living door was open (steam iron II) the decay
292 rate was faster than that under minimum ventilation conditions. The average particle
293 number concentration in the room was lower during the operation of the steam iron with
294 the living room door open ($1.7 \pm 0.092 \times 10^5 \text{ particles cm}^{-3}$). Steam ironing (2.6 ± 0.22
295 $\times 10^5 \text{ particles cm}^{-3}$) and steam ironing with boiler ($2.4 \pm 0.069 \times 10^5 \text{ particles cm}^{-3}$)
296 with the doors closed led to similar average particulate number concentrations in the
297 room. The ratios of peak to background levels for ultrafine particle number concentrations
298 indicate that ironing can elevate levels by a factor ranging from 35 to 194. The higher
299 ratios for particulate number concentrations in comparison with particulate mass
300 concentrations in similar conditions could be due to the increase of ultrafine particles
301 released during the ironing activity. The peak concentrations obtained in the present study
302 are much higher than those reported by Ciuzas et al. [42]. The researchers conducted the
303 source assessment in a test chamber representing a typical room (volume = 35.8 m^3) and

304 reported peak concentrations ranging from $3 \pm 0.58 \times 10^3$ to $36 \pm 6 \times 10^3$ particles cm^{-3}
 305 and from $19 \pm 2.4 \times 10^3$ to $28 \pm 4 \times 10^3$ particles cm^{-3} during ironing with and without
 306 steam, respectively (particles from 0.01 to 0.3 μm). Lower peak concentrations were
 307 reported by Afshari et al. [30], ranging from 0.55×10^3 particles cm^{-3} (flat iron without
 308 steam) to 7.2×10^3 particles cm^{-3} (flat iron with steam) (particles from 0.02 to 1.0 μm).
 309 A previous study conducted by Wallace and Ott et al. [31] in the basement of an American
 310 household documented peak concentrations in the range from 21×10^3 to 148×10^3
 311 particles cm^{-3} (particles from 0.01 to 1.0 μm).

312



313 Fig. 2. Particle number concentrations during ironing.

314

315 The maximum particle number concentrations detected by Ciuzas et al. [42] and Afshari
 316 et al. [30] were much lower than the ones obtained in the present study. The discrepancy
 317 is probably because only one cotton sheet was ironed in their studies in comparison with
 318 the vast array of clothing and linen ironed in this work.

319 In addition to the fact that only a small number of studies assessed the impact of this
320 source on indoor air quality, it should be borne in mind that differences in sampling
321 conditions (laboratory chambers vs on site measurements), devices employed to measure
322 the particle concentrations, size ranges, test conditions, as well as the chosen irons and
323 the operation mode (e.g. steam ironing versus ironing without steam) make the
324 comparison between studies difficult. In fact, Afshari et al. [30] observed that ironing a
325 cotton sheet with steam generated 10 times more particles than ironing without steam.
326 The authors hypothesised that the higher generation of particles during steam ironing
327 could be ascribed to (i) the expulsion of burned fibres from the cotton sheet due to the
328 steam or (ii) the formation of new particles by homogeneous nucleation during the cooling
329 of the water vapour from the steam.

330 In the present study, the average emission rates (particles from 0.008 to 0.322 μm) were
331 estimated to range from 8.1×10^{11} to 15×10^{11} particles min^{-1} (Table 1). Wallace and Ott
332 et al. [31] reported emission rates from steam ironing ranging from 0.4×10^{11} to $3.5 \times$
333 10^{11} particles min^{-1} (particles from 0.01 to 1.0 μm). The assessment of ironing a cotton
334 sheet in a full-scale chamber carried out by Afshari et al. [30] resulted in lower emission
335 rates ranging from 0.007×10^{11} particles min^{-1} (flat iron without steam) to 0.06×10^{11}
336 particles min^{-1} (flat iron with steam) (particles from 0.02 to 1.0 μm).

337 When ironing clothes using the steam iron, keeping the living room door closed, more
338 than 60% (64–69%) of the total particle number concentrations was found in the Aitken
339 mode ($30 < N < 100$ nm). This value dropped to 59–63% when the doors were opened
340 (condition II). The use of the steam iron with boiler also generated the highest number of
341 particles in the Aitken mode (61–62%). The geometric mean diameter (GMD) of the
342 particle size distribution ranged between 41.1 and 62.6 nm, while the source was active.
343 After switching off the iron, an increase of the GMD of the ultrafine particle mode was
344 observed in all experiments.

345

346 **3.3. Elements**

347 The PM_{10} mass fractions of 26 elements analysed in samples collected during ironing, and
348 in the background air sample, are shown in Table 2. Cl, Si and Na were the most abundant
349 inorganic elements found in the samples from steam ironing (conditions I and II), while
350 during the operation of the steam iron with boiler the dominant elements were Si, Al and
351 Cl. Elements accounted for PM_{10} mass fractions of 12, 14 and 5.5 %wt., which

352 represented increases over background levels of 2.6, 3.0 and 1.2 times for steam iron I,
 353 steam iron II and steam iron with boiler, respectively.

354

355 Table 2. PM₁₀ mass fractions (wt.%) of major and trace elements.

Element	Steam Iron - I	Steam iron - II	Steam iron with boiler	Background
Na	1.9	2.6 ± 0.036	0.48 ± 0.14	1.05
Mg	0.81	0.94 ± 0.030	0.19 ± 0.014	0.15
Al	0.92	1.0 ± 0.50	0.71 ± 0.21	0.31
Si	2.3	2.5 ± 1.2	2.4 ± 0.55	0.68
P	0.021	0.028 ± 0.016	0.012 ± 0.006	0.013
S	0.73	0.89 ± 0.16	0.22 ± 0.003	0.65
Cl	3.0	3.2 ± 0.11	0.61 ± 0.099	0.75
K	0.61	0.78 ± 0.056	0.15 ± 0.014	0.34
Ca	1.4	1.4 ± 0.62	0.60 ± 0.12	0.40
Ti	0.14	0.13 ± 0.047	0.030 ± 0.004	0.006
V	0.0003	0.001 ± 0.000	bdl	bdl
Cr	0.002	bdl	0.001 ± 0.001	0.005
Mn	0.006	0.010 ± 0.006	0.001 ± 0.001	0.007
Fe	0.30	0.39 ± 0.24	0.11 ± 0.004	0.26
Ni	0.001	0.002 ± 0.000	bdl	0.001
Cu	0.006	0.014 ± 0.003	0.009 ± 0.009	0.012
Zn	0.031	0.043 ± 0.011	0.013 ± 0.001	0.049
As	0.001	bdl	bdl	0.004
Se	0.0001	bdl	bdl	0.003
Br	0.021	0.011 ± 0.005	0.016 ± 0.000	0.002
Rb	0.002	0.002 ± 0.003	bdl	bdl
Sr	0.011	0.014 ± 0.009	0.007 ± 0.001	bdl
Y	0.0003	bdl	bdl	0.003
Zr	0.002	bdl	0.003 ± 0.003	bdl
Mo	bdl	bdl	bdl	bdl
Pb	bdl	0.014 ± 0.009	bdl	bdl
Σ Elements	12	14 ± 2.6	5.5 ± 1.1	4.7

356 bdl – below the detection limit.

357

358 Although several elements made up a small part of the PM₁₀ mass, the increase in
 359 concentration over the background level was noticeable. This was observed for Br (9–51
 360 times) and Ti (18–98 times). Additionally, Sr was only detected in the samples collected
 361 when the source was active.

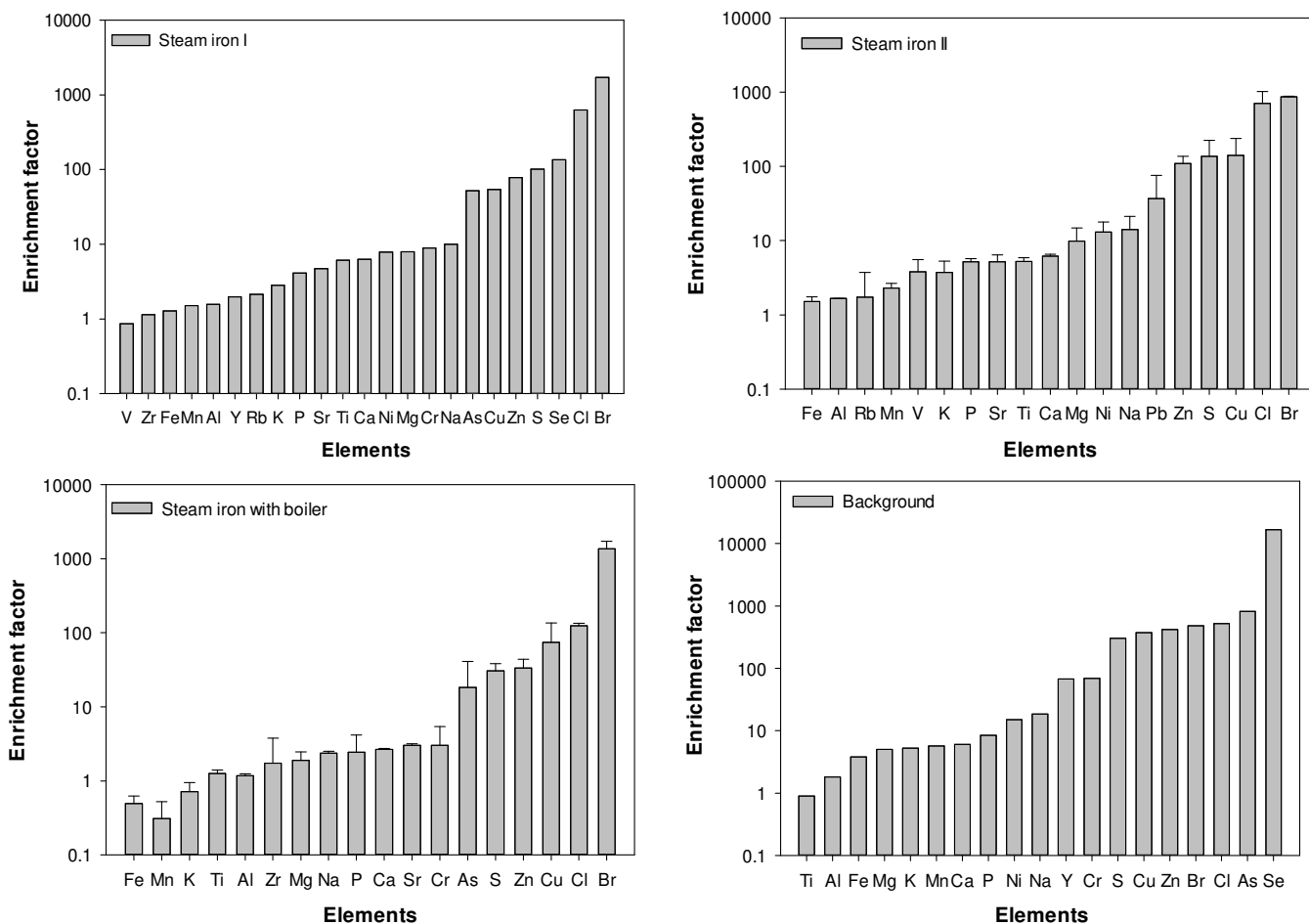
362 As reviewed by Licina et al. [73], trace elements, including heavy metals, are among the
 363 chemicals found in clothing. These can result from the manufacturing process (e.g.,
 364 dyeing, bleaching, finishing) or have been added to achieve a specific function (e.g.

365 control microbial activity, shield against UV radiation, enhance water repellence).
366 Clothing additives include nanomaterials, such as titanium dioxide (TiO₂), zinc oxide
367 (ZnO), copper and carbon nanotubes [73]. The type of material and colour are important
368 factors regarding the elemental content in clothing [74,75]. Rovira et al. [75] reported
369 high levels of Cr in polyamide dark clothes, high Sb concentrations in polyester clothes,
370 and high Cu levels in some green cotton fabrics. Turner [74] detected Br in clothing and
371 laundry dryer lint from natural and synthetic garments, suggesting that this element was
372 derived from clothing fibres. Brominated compounds are used in textiles as flame
373 retardants and used as disperse dyes [74].

374 Enrichment factors close to the unity (Fig. 3) for elements such as V, Zr, Fe, Mn, Al, Rb
375 and K, indicate a predominant natural contribution. Additionally, low EFs ($5 < EF < 10$)
376 were registered for Ca, Mg, Ti and P. Several of these elements (e.g. Al, Ca, Fe, insoluble
377 fractions of K, Mg and Na) have been generally associated with mineral dust [76,77]. In
378 the present study, very good correlations were obtained between K, Mg and Na ($r^2 >$
379 0.96). These elements also correlated well with Ti ($r^2 > 0.83$) and Zn ($r^2 > 0.84$) and
380 showed moderate correlations with Mn ($r^2 > 0.51$), Fe ($r^2 > 0.58$), Ca ($r^2 > 0.59$) and Ni
381 ($r^2 > 0.67$). These strong relationships suggest the existence of common sources for these
382 elements, probably resuspension of previously deposited dust (e.g. soil dust brought in
383 the shoes or dust particles deposited on clothing).

384 In the present study, other elements like Cu ($54 < EF < 141$), S ($31 < EF < 136$) and Zn
385 ($313 < EF < 109$) were enriched in PM₁₀ from all ironing tests. Bromide ($862 < EF <$
386 1712) and Cl ($124 < EF < 702$) were highly enriched in all the ironing samples (Fig. 3).
387 A strong correlation was found between the concentrations of Cl and S ($r^2 > 0.95$). The
388 occurrence of these elements in the PM₁₀ samples may derive from cleaning products
389 since they are part of the composition of these consumer items. In addition to the presence
390 in the background air, the contamination of the clothes during cleaning activities and the
391 ineffectiveness of washing in removing these metallic constituents, may justify the higher
392 concentrations in the particles resulting from ironing. Regarding Br, the only correlations
393 were found with Cr ($r^2 = 0.54$), Al ($r^2 = 0.68$) and Si ($r^2 = 0.76$). Moreover, only three of
394 the analysed elements displayed strong correlation with PM₁₀ concentrations: Al ($r^2 =$
395 0.70), Si ($r^2 = 0.87$) and Br ($r^2 = 0.96$). As far as we know, the elemental composition of
396 particles released during ironing has never been examined.

397



398

399 Fig. 3. Enrichment factors of elements in PM₁₀ sampled during ironing.

400

401 In the present study, we hypothesised that the occurrence of these elements in the PM₁₀
 402 samples might be associated with their evaporation from clothing when subjected to high
 403 temperatures during ironing and subsequent condensation on the surface of pre-existing
 404 particles. Garment handling during the activity can also release fibres, which contributes
 405 to the migration of elements into the air. In addition to the use of brominated compounds
 406 as discussed above, Cr, Al and Si are also employed in the textile industry with different
 407 purposes. For example, silicon based compounds (flame retardants, antimicrobial agents,
 408 surfactants, water and oil proofing agents) are used in textile industry due to their unique
 409 surface properties [78,79]. Metal salts (e.g. chromium and aluminium) are used as
 410 mordant to improve the affinity between dyes and fibres; they can also produce different
 411 colours and improve the fastness of a dye [80]. Additionally, several metals, including
 412 chromium, are widely used in dyes [81].

413

414 **3.4. OC/EC**

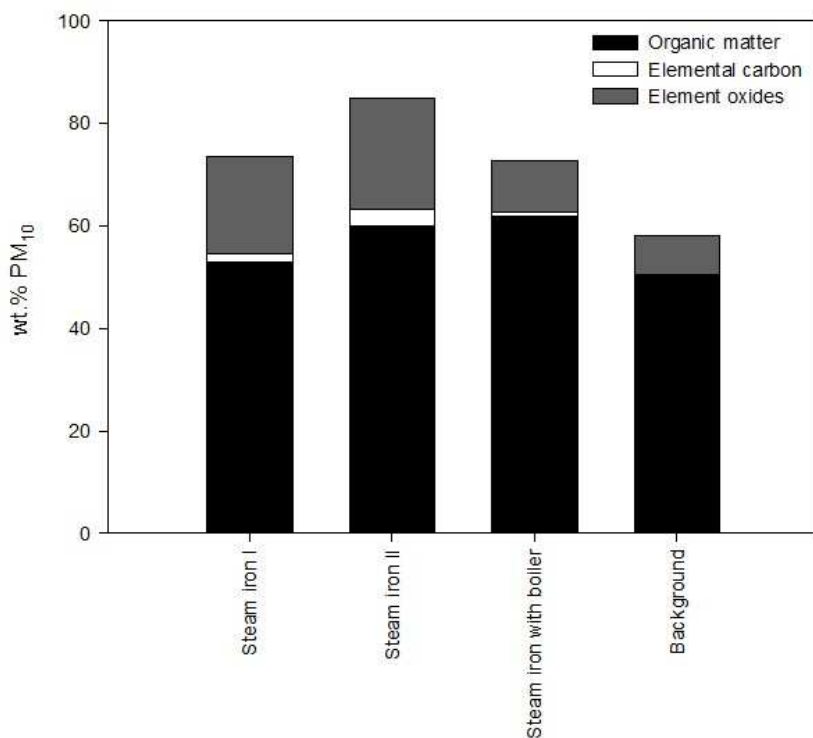
415 Total carbon (TC) represented from 30 ± 0.91 (steam iron I) to 34 ± 2.4 (steam iron with
416 boiler) %wt. of the PM_{10} mass during ironing and 28 ± 2.1 %wt. of the PM_{10} mass in the
417 background air. Elemental carbon (EC), not detected in the background sample,
418 comprised from 1.1 ± 0.2 to 3.1 ± 0.9 %wt. of the PM_{10} mass during ironing. The EC
419 increase over background may be attributable to burned fabric fibres released during
420 ironing. OC and EC concentrations in samples collected during ironing were not
421 correlated with each other, suggesting distinct sources. On the contrary, good correlations
422 were found between particulate OC concentrations and both Si ($r^2 = 0.81$) and Br
423 concentrations ($r^2 = 0.91$).

424 The OC particulate fractions in indoor settings can arise from a wide variety of sources.
425 In schools, several researchers have partially ascribed the PM organic content to clothing
426 fibres [82,83]. Additionally, household PM_{10} dust has been reported to contain
427 appreciable amounts of carbonaceous particles, mainly OC [84]. Although the handling
428 and ironing of clothes may constitute the major source of indoor carbonaceous
429 compounds found in PM_{10} samples, the possibility of other contributing sources cannot
430 be ruled out. Indoors, there are several sources of carbonaceous particles, both OC and
431 EC, such as cooking [17], vacuum cleaning [37,85], biomass burning for heating purposes
432 [22,47], cigarette smoking [45,86] and incense burning [46]. Despite the vast array of
433 possible sources, during the sampling campaign, the only activity that might have
434 contributed to the measured levels was cooking since none of the other activities took
435 place (carried out before ironing). In fact, as observed in the present study, despite the
436 temporary nature of indoor sources, they can release particles that remain for hours inside
437 the household [e.g. 36,37,87,88]. In cooking generated particles, organic carbon is the
438 major constituent and the release of OC and EC is closely related to the cooking method.
439 As reviewed by Abdullahi [17], indoor OC/EC ratios can vary between 4.3 and 7.7
440 depending on the method of food preparation. In the present study, higher OC to EC ratios
441 were recorded, ranging from 11 ± 4 (steam iron II) to 31 ± 7 (steam iron with boiler). The
442 mass closure between chemical and gravimetric measurements ranged from 58%
443 (background) to 85% (ironing) (Fig. 4). The unaccounted mass might be ascribed to
444 sampling and analysis artefacts, to PM_{10} -bound water and to unanalysed constituents.

445

446

447



448

449 Fig. 4. Chemical mass closure of PM₁₀.

450

451 3.5. Organic compounds

452 The detailed organic composition of PM₁₀ samples is presented in Table 3. The PM₁₀
 453 samples encompassed n-alkanes from C₁₁ to C₃₅, maximising at C₂₅ and C₂₇ for samples
 454 collected during ironing under minimum ventilation conditions. The carbon preference
 455 index (CPI), calculated for the whole range of n-alkanes, oscillated from 0.9 to 1.4
 456 denoting an input of n-alkanes derived from petroleum derivatives [89]. The presence of
 457 these compounds seems to be closely related to ironing, decreasing noticeably with the
 458 increase in the ventilation rates (steam iron II). In fact, opening the living room door
 459 decreased the Σ₂₅ n-alkane concentrations more than 3000 times. Steam ironing with
 460 boiler led to higher n-alkane concentrations (Σ₂₅ 2478 ng m⁻³) in comparison with steam
 461 iron (Σ₂₅ 1427 ng m⁻³) under similar ventilation conditions (minimum), representing an
 462 increase over background concentrations ranging from 82 to 143 times. In a previous
 463 study, assessing the impact of vacuuming on PM₁₀-bound organic compounds in the same
 464 room, much lower concentrations of n-alkanes were recorded (Σ₂₅ from 22.4 to 39.3 ng
 465 m⁻³ during vacuuming). The presence of these compounds was hypothesised to partially
 466 derive from oil-based or petrochemical textiles such as nylon, polyester, acrylic and
 467 spandex [85].

468

469 Table 3. Concentrations (ng m⁻³) of organic compounds in PM₁₀.

	Steam iron I	Steam iron II	Steam iron with boiler	Background
<i>Aliphatics</i>				
Undecane	5.98	nd	95.4	0.309
Dodecane	0.646	0.193	1.43	0.026
Tridecane	0.281	0.183	1.09	0.012
Tetradecane	0.132	nd	1.48	bdl
Pentadecane	1.08	nd	2.87	0.525
Hexadecane	0.733	nd	3.62	bdl
Heptadecane	bdl	nd	bdl	bdl
Octadecane	6.95	bdl	17.0	bdl
Nonadecane	14.4	bdl	32.2	bdl
Eicosane	25.6	bdl	58.4	1.39
Heneicosane	47.6	bdl	98.9	2.94
Docosane	70.2	bdl	138	5.96
Tricosane	111	bdl	211	5.15
Tetracosane	142	bdl	251	1.03
Pentacosane	180	bdl	311	bdl
Hexacosane	155	bdl	212	bdl
Heptacosane	174	bdl	317	bdl
Octacosane	134	nd	170	bdl
Nonacosane	131	nd	204	bdl
Triacontane	73.1	nd	88.2	bdl
Hentriacontane	79.8	nd	129	bdl
Dotriacontane	36.7	nd	57.8	bdl
Tritriacontane	13.4	nd	29.7	nd
Tetratriacontane	12.0	nd	32.0	nd
Pentatriacontane	11.1	nd	14.8	nd
Dodecene	2.07	nd	5.23	nd
Tetradecene	0.240	nd	4.38	bdl
Hexadecene	0.369	nd	0.947	0.429
Octadecene	nd	nd	nd	bdl
Eicosene	nd	nd	nd	bdl
Tricosene	18.7	0.050	18.5	0.291
Squalene	21.0	nd	33.2	0.351
<i>Saccharides and polyols</i>				
Levogluconan	15.1	23.1	5.59	22.1
Mannosan	nd	nd	nd	1.27
Ribitol	2.97	6.31	1.51	nd
D-glucuronic acid lactone	5.94	4.08	nd	nd
Quebrachitol	nd	nd	0.018	nd
Meso-Erythritol	nd	nd	nd	0.280
Other saccharides and polyols	135	82.9	14.4	3.82
<i>Triterpenoid and steroid compounds</i>				
Lupeol	nd	nd	nd	0.323

Cholesterol	734	766	2682	4.29
5-Cholesten-3-ol	9.57	48.3	94.5	nd
Stigmasterol	nd	nd	14.9	nd
β -Sitosterol	30.2	33.8	30.2	1.20
<i>Aliphatic alcohols</i>				
1-Nonanol	1.41	1.98	0.914	nd
1-Decanol	0.970	1.29	3.09	0.014
1-Dodecanol	29.7	115	122	7.02
1-Tetradecanol	114	348	431	8.78
1-Pentadecanol	165	407	298	32.9
C ₁₅ Alkanol isomers	7.20	31.3	7.95	3.65
1-Hexadecanol	691	675	909	82.9
C ₁₆ Alkanol isomers	3.13	16.1	7.44	1.39
1-Octadecanol	1046	689	2496	32.6
1-Nonadecanol	5.41	32.8	90.8	1.06
1-Eicosanol	nd	nd	115	nd
C ₂₀ Alkanol isomers	193	10.4	275	1.48
1-Heneicosanol	11.7	10.6	26.4	nd
1-Docosanol	64.4	43.4	137	bdl
1-Tricosanol	384	201	613	0.470
C ₂₃ Alkanol isomers	11.0	13.0	37.2	0.000
1-Tetracosanol	29.6	41.6	54.5	nd
1-Pentacosanol	4.89	4.87	9.34	0.035
C ₂₅ Alkanol isomers	23.4	22.2	51.7	nd
1-Hexacosanol	21.1	18.5	17.1	0.820
1-Heptacosanol	6.65	5.72	4.10	0.018
C ₂₇ Alkanol isomers	23.7	47.8	1.36	3.83
1-Octacosanol	667	578	382	0.094
1-Nonacosanol	0.394	5.76	nd	nd
1-Tricontanol	164	201	102	0.047
<i>Alkanoic acids</i>				
1-Heptanoic acid	nd	nd	5.64	nd
1-Octanoic acid	8.36	8.27	46.5	0.163
1-Nonanoic acid	31.8	29.1	225	0.194
1-Decanoic acid	44.4	34.2	137	0.323
1-Undecanoic acid	3.11	2.96	9.36	0.249
1-Dodecanoic acid	167	298	843	87.8
1-Tridecanoic acid	24.7	14.6	83.6	2.31
C ₁₃ Alkanoic acid isomers	19.7	nd	78.3	nd
1-Tetradecanoic acid	1636	1438	1524	165
C ₁₄ Alkanoic acid isomers	32.8	nd	62.1	nd
1-Pentadecanoic acid	592	351	1674	9.52
C ₁₅ Alkanoic acid isomers	254	5.74	678	nd
1-Hexadecanoic acid	3851	2075	5415	127
C ₁₆ Alkanoic acid isomers	149	9.12	381	nd
1-Heptadecanoic acid	282	230	434	1.73

C ₁₇ Alkanoic acid isomers	334	20.0	904	nd
1-Octadecanoic acid	1637	1263	4180	60.9
1-Nonadecanoic acid	9.74	6.35	6.70	0.109
1-Eicosanoic acid	123	51.6	248	0.443
C ₂₀ Alkanoic acid isomers	18.1	nd	46.7	nd
1-Heneicosanoic acid	8.83	nd	34.7	nd
C ₂₁ Alkanoic acid isomers	31.9	nd	59.8	nd
1-Docosanoic acid	65.3	25.4	111	1.76
1-Tricosanoic acid	23.7	5.06	38.8	nd
1-Tetracosanoic acid	120	54.8	261	0.285
1-Pentacosanoic acid	19.3	3.82	34.1	nd
C ₂₅ Alkanoic acid isomers	16.7	4.01	28.6	nd
1-Hexacosanoic acid	28.2	9.41	45.1	nd
C ₂₆ Alkanoic acid isomers	4.33	nd	4.63	nd
1-Octacosanoic acid	8.07	2.85	10.7	nd
1-Triacontanoic acid	2.10	nd	3.33	nd
<i>Alkenoic acids</i>				
9-Tetradecenoic acid	27.0	nd	80.1	nd
Pentadecenoic acid	28.7	nd	80.6	nd
9-Cis-hexadecenoic (palmitoleic) acid	701	416	1925	1.43
10-Heptadecenoic acid	150	nd	364	nd
Cis-9-octadecenoic (oleic) acid	1821	1661	4795	20.4
Cis,cis-9-12-octadecadienoic (linoleic) acid	282	127	447	1.43
10-Nonadecenoic acid	7.11	nd	24.3	nd
Eicosenoic acid	27.1	nd	53.8	nd
<i>Alkanedioic acids</i>				
1,4-Butanedioic (succinic) acid	1.26	2.79	6.99	1.05
1,5-Pentanedioic (glutaric) acid	7.51	20.8	bdl	4.18
Hexanedioic (adipic) acid	6.33	6.69	59.1	2.05
Heptanedioic (pimelic) acid	0.496	0.546	1.08	0.248
Octanedioic (suberic) acid	2.23	1.28	7.42	0.251
Nonanedioic (azelaic) acid	9.67	5.22	57.8	0.885
Decanedioic (sebacic) acid	1.23	1.05	nd	nd
<i>Other acids</i>				
4-Oxopentanoic (levulinic) acid	21.0	27.7	89.1	nd
2,3-Dihydroxypropanoic (glyceric) acid	6.85	8.34	nd	14.6
3-Hydroxybutanoic (3-hydroxybutyric) acid	0.274	0.455	0.478	0.166
2-Hydroxy-butanedioic (L-(-)-malic) acid	0.433	1.51	nd	nd
Hexanedioic (adipic) acid dibutyl ester	16.4	45.7	14.5	12.2
Cis-Pinonic acid	0.238	0.356	nd	0.302
Pinic acid	nd	1.42	nd	nd
Citric acid	0.082	0.12	nd	0.088
Dehydroabiatic acid	0.194	0.980	5.06	0.485
Isopimaric acid	2.85	1.33	nd	0.009
Abietic acid	0.234	0.152	nd	nd
Podocarpic acid	nd	nd	nd	0.003

<i>Alkyl esters of fatty acids</i>				
Tetradecanoic acid 1-methylester	45.3	27.3	147	25.2
Hexadecanoic acid, methyl ester	65.9	46.3	280	63.2
Hexadecanoic acid, ethyl ester	4.45	2.75	15.2	1.32
Hexadecanoic acid, isopropyl ester	247	144	652	60.8
Hexadecanoic acid, hexadecyl ester	19.5	18.6	89.8	nd
Dodecanoic acid, isooctyl ester	20.4	20.1	48.6	7.42
Octadecanoic acid, methyl ester	62.9	22.9	238	12.7
Hexanoic acid 2-ethyl-, hexadecyl ester	25.8	23.1	198	1.96
Hexanedioic acid, dioctyl ester (dioctyl adipate)	nd	181	206	7.23
Octanoic acid, hexadecyl ester	10.0	12.8	98.6	0.173
<i>Phenolics and alteration products</i>				
Pyrocatechol	0.011	0.009	0.028	bdl
5-Isopropyl-3-methylphenol	0.107	0.235	0.579	bdl
Resorcinol	0.024	0.028	0.323	0.013
4-Methyl catechol	0.016	0.007	0.038	0.001
2,6-Dimethoxyphenol	0.029	nd	nd	0.001
Eugenol	0.030	0.017	0.066	0.001
4-Allyl-2,6-dimethoxyphenol (methoxy eugenol)	nd	nd	nd	0.010
Pyrogallol	0.007	0.009	0.012	0.001
Isoeugenol	0.941	1.83	2.14	bdl
2-Methoxy-4-propylphenol	0.441	0.716	0.833	nd
4-Phenylphenol	nd	nd	nd	0.005
4-Octylphenol	0.303	0.024	0.464	0.006
2,4-Di-tert-butylphenol	69.8	112	108	20.6
Sinapyl alcohol	0.012	0.012	nd	0.001
Benzyl alcohol	16.7	43.4	55.1	bdl
Benzoic acid	0.234	0.797	13.8	0.187
4-Hydroxybenzoic acid	0.263	0.360	1.09	0.074
Benzoic acid alkyl esters	239	126	1160	12.6
Trans-cinnamic acid	0.224	0.316	bdl	0.027
Vanillic acid	0.021	0.016	bdl	0.031
Syringic acid	0.023	0.040	bdl	0.054
Sinapic acid	nd	0.112	nd	nd
4-Hydroxy-3-methoxycinnamic (ferulic) acid	nd	nd	nd	nd
4-Hydroxycinnamic (p-coumaric) acid	0.198	0.086	nd	nd
4-Tert-butylphenol	4.12	8.29	14.3	1.71
Bisphenol A	90.5	17.4	60.9	5.43
<i>Glycerol derivatives</i>				
Glycerol	804	788	783	143
1-Monolauroyl-rac-glycerol	nd	0.028	nd	nd
Ethylene glycol palmitate	76.1	36.2	151	nd
1-Monomyristin	323	61.8	528	nd
Glyceryl pentadecanoate	164	51.0	496	nd
1-Monopalmitin	709	635	1896	3.50
1-Hexadecyl glycerol	8.09	nd	nd	nd

Glycerol, mono-heptadecanoate	10.9	nd	21.3	nd
2-Monolinolein	51.7	9.39	170	nd
2-Oleoylglycerol (2-monoolein)	50.4	nd	103	nd
1-Monolinoleoylglycerol	741	652	2074	nd
1-Glycerol monostearate (1-monostearin)	339	197	944	4.59
Glycerol tricaprilate	32.3	42.1	36.2	nd
<i>Plasticisers</i>				
Benzyl butyl phthalate	36.0	67.1	150	5.68
Bis(2-ethylhexyl)adipate	0.230	nd	1.83	bdl
Bis(2-ethylhexyl)phthalate	bdl	bdl	1.65	bdl
Di-n-butyl phthalate	bdl	0.095	0.030	bdl
Dimethyl phthalate	0.004	0.016	0.033	0.010
Diethyl phthalate	15.1	5.08	41.8	49.6
Unidentified phthalates	2437	3435	8763	253
<i>Other compounds</i>				
Diethylene glycol	28.3	56.9	22.0	nd
1,2,3-Hexanetriol	0.102	nd	0.223	nd
2,6-Di-tert-butyl-p-benzoquinone	0.994	0.089	2.53	0.214
(S)-(-)-b-Citronellol	nd	nd	11.4	nd
α -Hexylcinnamaldehyde	14.3	1.80	17.2	0.211
2-Propanol-1-chloro-phosphate (TCPP)	nd	42.3	58.7	12.5
Acetyl tributyl citrate	17.5	30.9	27.1	3.25
(1S, 2S, 3R, 5S)-2,3-Pinandediol	nd	nd	0.373	0.064
Tocopheryl acetate	1913	98.0	493	nd
Diethyltoluamide (DEET)	47.5	164	69.6	43.3
Parsol MCX	207	91.7	351	5.43
Oxidised Irgafos 168	21.4	bdl	nd	29.4
Irganox 1076	nd	65.3	12.1	nd
Methyl dihydrojasmonate	5.93	nd	nd	nd
7,9-Di-tert-butyl-1-oxaspiro[4.5]deca-6,9-diene-2,8-dione	5.76	nd	nd	nd
Benzothiazole	0.052	0.030	0.094	nd
Butylphenyl methylpropional (Lilial)	1.20	0.460	6.13	0.067
<i>PAHs</i>				
Naphthalene	0.288	0.236	0.643	bdl
Acenaphthene	0.007	0.009	0.036	0.001
Fluorene	bdl	bdl	0.197	bdl
Phenanthrene	0.183	0.067	0.513	0.170
Anthracene	bdl	bdl	0.048	0.119
Acenaphthylene	0.405	0.093	0.355	nd
Retene	0.534	0.192	1.03	0.097
Fluoranthene	0.236	0.124	0.592	0.090
Pyrene	0.274	0.111	0.774	0.525
Chrysene	0.117	0.050	1.56	0.393
Benzo[a]anthracene	bdl	bdl	1.70	0.392
Benzo[b]fluoranthene	0.496	bdl	0.929	0.392

Benzo[k]fluoranthene	nd	0.173	0.607	0.333
Benzo[e]pyrene	0.120	0.283	0.151	0.162
Benzo[a]pyrene	0.021	bdl	0.970	0.145
Perylene	nd	0.031	0.026	nd
Dibenzo[a,h]anthracene	bdl	0.010	0.096	0.105
Indeno[1,2,3-cd]pyrene	0.039	0.200	2.51	0.194
Benzo[g,h,i]perylene	0.051	0.257	0.389	0.199

470 bld – below the detection limit; nd - not detected.

471

472 Alkenes were also detected in some samples at low concentrations. Squalene, a
 473 constituent of skin oil, was detected in the PM₁₀ samples at concentrations ranging from
 474 21.0 to 33.2 ng m⁻³ in the samples collected under minimum ventilation conditions, while
 475 it was not detected during steam ironing with the living door open (condition II).

476 In the present study, several saccharides and polyols were identified in samples.
 477 Levoglucosan was the most abundant compound in this organic class and was present
 478 both during ironing (5.59–23.1 ng m⁻³) and in the background air (22.1 ng m⁻³).
 479 Levoglucosan derives from the thermal decomposition of cellulose [90].

480 Within terpenoids and sterols, cholesterol was the most abundant compound. It was
 481 detected at higher concentrations during ironing (734–2682 ng m⁻³) in comparison with
 482 background (4.29 ng m⁻³) (Table 3). Cholesterol has been reported in emissions from
 483 cooking activities [17] and it is also present as epidermal lipid [91]. In fact, a previous
 484 study carried out in children bedrooms and day care centres documented the presence of
 485 cholesterol in dust, pointing out desquamated skin cells, cooking, skin care products and
 486 outdoor-to-indoor transport of cholesterol-containing particles as probable sources [92].
 487 β-sitosterol, the second major sterol found in the present study during ironing (30.2–33.8
 488 ng m⁻³) and in the background sample (1.20 ng m⁻³), has also been detected in Chinese
 489 cooking (vegetables) emissions [93].

490 Alcohols from C₉ to C₃₀ were detected in the PM₁₀ samples (Table 3). The Σ₁₉ alkanol
 491 concentrations ranged from 3521 to 6192 ng m⁻³ during ironing, whereas a much lower
 492 level (177 ng m⁻³) was observed in the background air. 1-Octadecanol and 1-hexadecanol
 493 were the most abundant alcohols, followed by 1-octacosanol and 1-tricosanol. Their
 494 concentrations during ironing were from 8 to over 1000 times higher than those measured
 495 in background air. Alkanols, typically with a chain length of C₁₀ and higher, are widely
 496 employed in personal care and cosmetic products, as well as in household products,
 497 including laundry detergents and fabric softeners [94].

498 Twenty-two saturated fatty acids from C₇ to C₃₀, maximising at C₁₄ (myristic), C₁₆
499 (palmitic) or C₁₈ (stearic) were identified in PM₁₀ samples (Table 3). The Σ₂₂ alkanolic
500 acid concentrations ranged from 5942 to 17,614 ng m⁻³ during ironing, while the
501 background air sample presented a concentration of 458 ng m⁻³. Alkanolic acids are
502 ubiquitous compounds from multiple sources [17,95]. In the present study, alkenolic acids
503 were also found in PM₁₀ samples. The highest concentrations were recorded for
504 palmitoleic acid and oleic acid. Unsaturated fatty acids, such as oleic, linoleic and
505 palmitoleic acids, have been described in cooking emissions [17]. Fatty acids, such as
506 oleic, palmitic, stearic, linoleic and myristic acids, are also included in the list of chemical
507 formulations of cosmetic products [96]. n-Alkanedioic acids were also identified in the
508 PM₁₀ samples (Table 3). Dicarboxylic acids may have various origins, including
509 photochemical reactions [17,95,97,98].
510 Other acids were also detected in the PM₁₀ samples. The most abundant was levulinic
511 acid (21.0–89.1 ng m⁻³), which has been described as an oxidant product of skin oils [99].
512 This keto acid is also used in a variety of applications, including personal care products
513 [100]. This compound was previously detected indoors in a university cafeteria during
514 the working hours (occupancy period) with an average concentration of 13.2 ± 9.6 ng m⁻³
515 [101].
516 Glycerol and several derivatives were present in the PM₁₀ samples. Glycerol is a major
517 breakdown product of triglycerides during meat cooking [17]. It was present in samples
518 collected during ironing (783–804 ng m⁻³) and in background (143 ng m⁻³). In cosmetics,
519 this polyol is widely employed as solvent and humectant [96].
520 Alkyl esters of fatty acids were also present in the PM₁₀ samples. The highest
521 concentrations were recorded for isopropyl palmitate (hexadecanoic acid, isopropyl
522 ester), methyl palmitate (hexadecanoic acid, methyl ester) and dioctyl adipate
523 (hexanedioic acid, dioctyl ester). Among other possible origins, isopropyl palmitate and
524 methyl palmitate can be released indoors from the use of laundry detergents, fragrances
525 and air fresheners [102,103]. Dioctyl adipate is used as a plasticiser and, among many
526 other applications, it is employed in textile spin finishes and pigment wetting agent [104].
527 The most abundant phenolic compounds detected in the samples were benzoic acid alkyl
528 esters, bisphenol A, 2,4-di-tert-butylphenol, benzyl alcohol and 4-tert-butylphenol.
529 Benzoic acid and a wide range of derivatives, such as alkyl esters, are widely used in
530 different industrial sectors (e.g. flavouring agents in food, cosmetic and hygiene products)
531 [105]. Bisphenol A (BPA) has been detected in newly purchased infant clothing [106]

532 and also in washed clothes [107]. Wang et al. [107] investigated the occurrence of
533 bisphenol chemicals in daily clothes. The maximum concentrations of BPA were detected
534 in new garments. It was also demonstrated that laundry cannot remove BPA efficiently
535 but cause cross contamination in clothes. BPA is not used directly in textile production
536 but is employed as an intermediate chemical in the manufacture of antioxidants and dyes
537 [106, and references therein]. In the present study, this compound was found in all
538 samples during ironing (17.4–90.5 ng m⁻³) and in the background air (5.43 ng m⁻³). As
539 reviewed by Licina et al. [73], a wide range of organic compounds have been detected in
540 clothing, including alkylphenols and alkylphenol ethoxylates. In fact, an indoor source of
541 alkylphenols might be attributed to the biodegradation of alkylphenol ethoxylate, which
542 is a widely used surfactant in laundry detergents [108]. Phenylpropenes, such as eugenol
543 and isoeugenol, were also detected in the samples, although at low concentrations. These
544 compounds are fragrance materials commonly used in household products, such as
545 detergents [109], consumer products (e.g. air fresheners) [110] and also in a wide range
546 of cosmetics and toiletries [111].

547 Fragrance compounds are likely to be found in clothes and other textiles, especially after
548 laundering, due to the use of detergents and fabric softeners [111]. Butylphenyl
549 methylpropional (lilial) and α -hexylcinnamaldehyde, compounds used as fragrance
550 ingredients in laundry detergents and softeners [112,113], were detected in all samples.
551 Their concentrations were from 7 to 91 times higher than in background air. Other
552 fragrance components were detected in some of the analysed samples such as citronellol,
553 which has been found in the composition of cosmetics and toiletries [111], and also
554 methyl dihydrojasmonate, widely used in cleaning and personal care products [114]. The
555 use of cosmetic and personal care products was also evidenced by the presence of Parsol
556 MCX, a common ingredient in sunscreen personal care products [115]. During ironing,
557 the concentrations of this compound oscillated from 5.43 to 351 ng m⁻³.

558 Other hydroxyl compounds were detected in the particulate matter organic extracts.
559 Among these, diethyltoluamide (DEET) was found in all samples, including in
560 background air, in concentrations ranging from 43.3 to 164 ng m⁻³. This compound is
561 used as insect repellent in various topical forms containing between 10 and 95% of DEET
562 [111]. 2-Propanol-1-chloro-phosphate (TCPP), a common phosphorous organic flame
563 retardant [116], was found in the background sample and in two of the samples collected
564 during ironing (12.5–58.7 ng m⁻³). Irganox 1076 and Irgafos 168, which are employed as
565 antioxidants in the manufacture of plastics [117], were also detected in some of the

566 analysed samples. Diethylene glycol is a toxic compound used in some dyes [118]. This
567 compound was only found in samples collected during ironing in concentrations ranging
568 from 22.0 to 56.9 ng m⁻³. Benzothiazole was found in PM₁₀ samples collected during
569 ironing in concentrations ranging from 0.03 to 0.09 ng m⁻³, whereas it was absent from
570 the background air sample. This compound has been found previously in clothing textiles
571 (present in 23 of 26 investigated garments) in concentrations ranging from 0.45 to 51 µg
572 g⁻¹ textile [119]. Acetyl tributyl citrate, a citric acid ester, is widely used as plasticiser in
573 cosmetics and also in non-cosmetic applications, such as vinyl, coatings and adhesives,
574 including the ones intended to be taken as components of articles for packaging,
575 transporting or holding food [120]. This compound was detected in the PM₁₀ samples
576 collected during ironing (17.5–30.9 ng m⁻³) and in background air (3.25 ng m⁻³). Other
577 plasticisers were present in PM₁₀ samples. Benzyl butyl phthalate, diethyl phthalate and
578 dimethyl phthalate were detected in all samples, including background. Benzyl butyl
579 phthalate had the highest concentrations showing an increase over background
580 concentrations ranging from 6 to 26 times. Additionally, during steam ironing with boiler
581 bis(2-ethylhexyl)adipate, bis(2-ethylhexyl)phthalate and di-n-butyl phthalate were also
582 detected in concentrations ranging from 0.033 to 1.83 ng m⁻³.

583 The Σ₁₉ PAHs concentrations ranged from 1.84 (steam iron II) to 13.1 ng m⁻³ (steam iron
584 with boiler) during ironing and 3.32 ng m⁻³ in the background air (Table 3). The measured
585 PAH concentrations are comparable to those observed in previous studies conducted in
586 European residential settings [121,122]. The congeners with highest concentrations
587 during ironing were retene, benzo[e]pyrene and indeno[1,2,3-cd]pyrene.

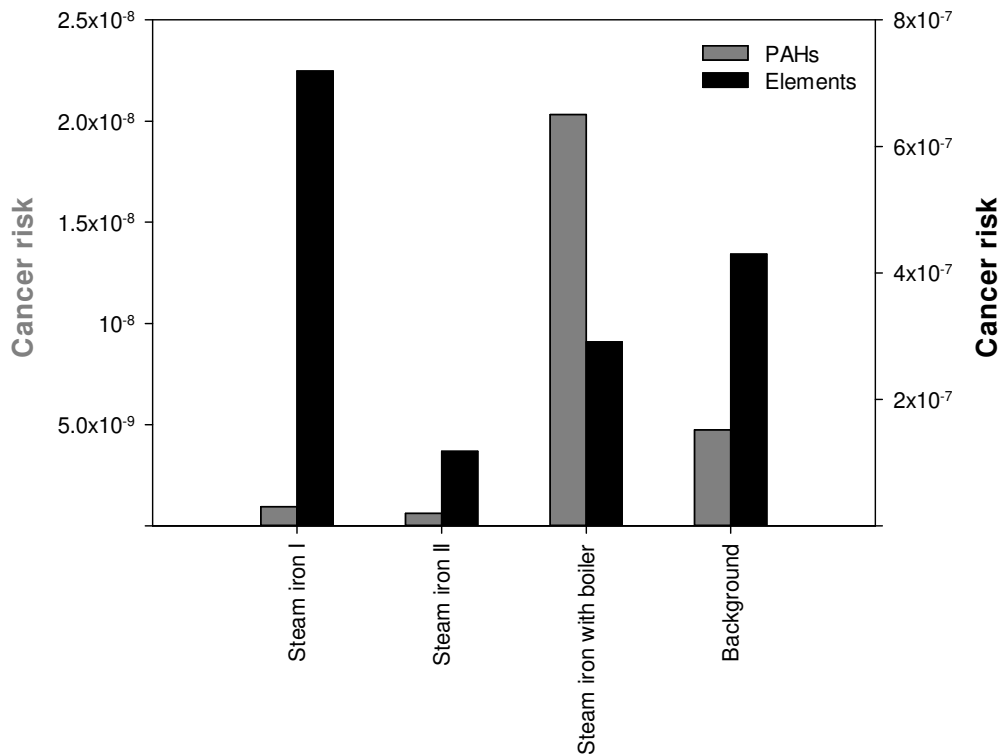
588

589 **3.6. Health risk assessment**

590 Household chores, such as ironing, make up an important part of everyday life and can
591 be responsible for human exposure to hazardous pollutants, such as particulate matter and
592 its constituents. Toxicity is related to constituents that are chemically bound to particles
593 in the respirable size range, some of which classified by the IARC as Group 1
594 carcinogens, after establishing causal relationships between exposure to these agents and
595 human cancer. Among the PM-bound constituents, As, Cr (VI), Pb, Co, Cd, Ni and
596 benzo[a]pyrene can pose a threat to human health since they have been classified by the
597 IARC as Group 1 based on “sufficient evidence” of carcinogenicity in humans.

598 The additional risks of developing cancer due to inhalation exposure during ironing to
599 carcinogenic elements (As, Cr (VI), Pb, Co, Cd and Ni) over the lifetime of an individual

600 (assumed to be 70 years) were found to be negligible (always $< 7.2 \times 10^{-7}$) with respect
 601 to the acceptable risk (lower than 1×10^{-6}) (Fig. 5). The noncancer hazard quotients (HQ)
 602 associated with inhalation exposure by households to particulate trace elements in the
 603 indoor air during ironing were much lower than unity (safe limit), indicating negligible
 604 risks.
 605



606
 607 Fig. 5. Excess cancer risk for inhalation exposure to PAHs and elements.

608
 609 In the present study, the average concentrations of PAH (expressed as BaP equivalent
 610 concentration) ranged from 0.05 to 1.66 ng m⁻³ for the steam iron (condition II) and steam
 611 iron with boiler, respectively. The resulting excess lifetime lung cancer risks for the
 612 exposed person were 6.2×10^{-10} and 2.0×10^{-8} (Fig. 5), i.e. much lower than the
 613 acceptable level of 10^{-6} .

614 Although the cancer risk and non-cancer hazard quotient associated with exposure to
 615 PM₁₀ from ironing through the inhalation pathway were found to be negligible, it is
 616 necessary to bear in mind that, in contrast to the short period of exposure to this domestic
 617 task, laundry/ironing workers are occupationally exposed during long working hours, so
 618 this activity can represent a danger for these professionals.

619

620 **4. Conclusions**

621 The present study aimed to obtain number and mass concentrations, as well as to detail
622 the chemical composition, of particulate matter emitted during ironing with different
623 appliances (steam iron and steam iron with boiler) and under distinct conditions
624 (condition I: steam iron and steam iron with boiler with the room door closed, and
625 condition II: steam iron with indoor living room door open). Despite the transient nature
626 of this source, it generated high peaks of particle number and mass concentrations. The
627 greatest effect was observed for particle number concentrations (8–322 nm) with average
628 increases from 33 to 72 times over background levels. The increase in PM₁₀ mass
629 concentrations ranged, on average, from 4 to 10 times over background levels. The
630 highest particulate mass and number emission rates were observed during steam ironing
631 with boiler, indicating that the steam pressure may play a role on particle generation. The
632 results highlighted the great variability in particle emission rates depending not only on
633 the equipment but also on the operator behaviour, suggesting that household exposure
634 can be enhanced or reduced by proper space ventilation and iron selection.

635 In the present study, a vast array of compounds was identified and quantified in the PM₁₀
636 samples, some of which may derive from shedding of fibres and volatilisation followed
637 by condensation of constituents of textile fabrics. Elemental carbon, not detected in the
638 background air, encompassed from 1.1 ± 0.2 to 3.1 ± 0.9 %wt. of the PM₁₀ mass during
639 ironing. Bromide was highly enriched in all the ironing samples. Although the
640 contribution of this element to the PM₁₀ mass was small, the increase in Br concentrations
641 over background values ranged from 9 to 51 times during ironing. The good correlations
642 between Br and Cr, Al and Si and between OC and both Si and Br concentrations suggest
643 a common source for these constituents. Many of the PM₁₀-bound organic compounds
644 detected are likely to originate in laundry detergents and softeners, as well as in
645 components incorporated during the textile manufacturing process (e.g. flame retardants).
646 Additionally, multiple compounds with other possible sources were also detected, such
647 as markers of cooking, ingredients of personal care products and plasticisers. The cancer
648 risk and non-cancer hazard quotient associated with household exposure to PM₁₀ from
649 ironing through the inhalation pathway were found to be negligible.

650 Although it needs to be supplemented with additional measurements, the database
651 obtained in this study is potentially useful to determine the contribution of ironing to the
652 indoor particulate matter levels through source apportionment models. Further

653 investigations, carried out under controlled laboratory environment, are necessary to
654 consolidate the conclusions.

655 **Declaration of competing interest**

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

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