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1 **Microplastics in the atmosphere of Ahvaz City, Iran**

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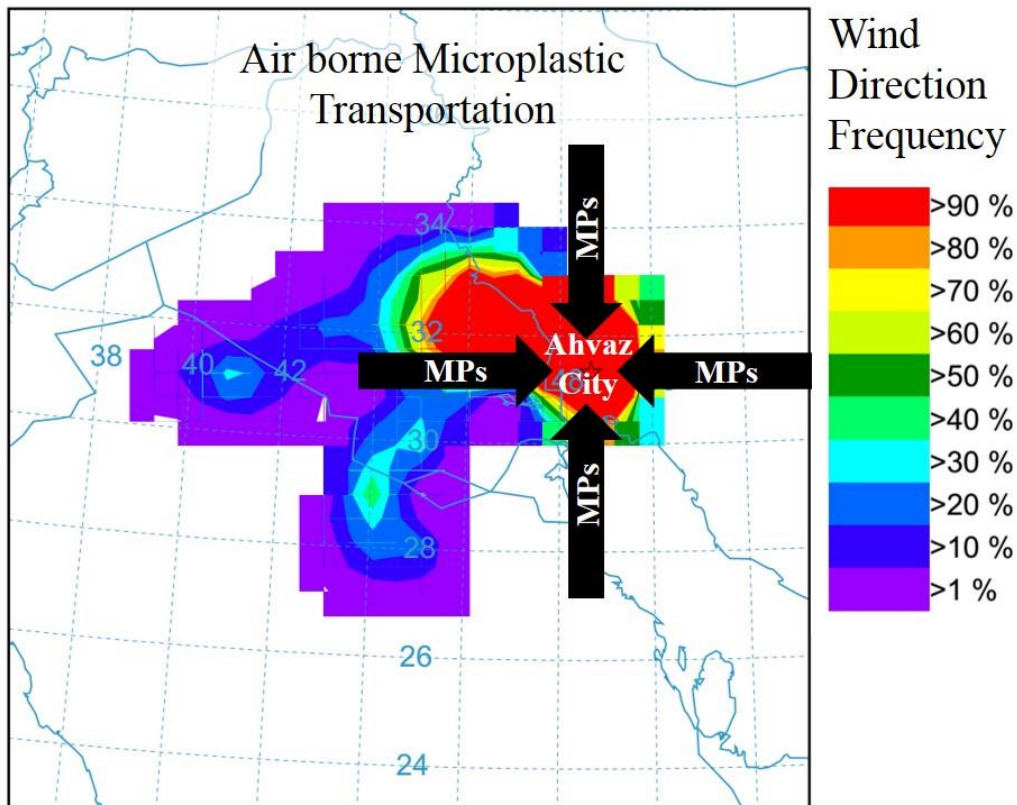
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30 **Graphical Abstract**



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33 **Highlights**

- 34 • Airborne particulate matter was collected from urban and industrial sites in Ahvaz.
- 35 • Microplastics (MP) were isolated from samples and characterised by established
- 36 techniques.
- 37 • All MP were fibrous and the dominant polymers were PET and polypropylene.

- 38 • Concentrations of MP ($< 0.017 \text{ m}^{-3}$) exhibited no clear temporal trends or inter-site
39 differences.
- 40 • Sample characteristics and trajectory modelling suggest both local and long-range
41 sources.

42 **Abstract**

43 Airborne particulate matter (PM) with an aerodynamic size cutoff of 10 μm (PM₁₀) has been
44 collected using a high volume air sampler at two locations (urban and residential) in the city of
45 Ahvaz, Iran, for sixteen 24-hour periods over four months (late summer to early winter).
46 Microplastics (MPs) in the PM were isolated after sample digestion and were subsequently
47 characterised by established techniques. All MPs sampled ($n = 322$) were of a fibrous nature,
48 with polyethylene terephthalate and polypropylene being the dominant polymers and consistent
49 with textiles and fabrics as the principal source. Despite a distinct seasonality (temperature and
50 wind) over the study period, the abundance, size and colour of the fibres exhibited no clear
51 temporal trend, and no clear differences were observed between the two sites. Concentrations
52 of MPs ranged from none detected to about 0.017 per m^3 (median = 0.0065 m^{-3}) and are at the
53 low end of ranges reported in the recent literature for various urban and remote locations. While
54 some MPs may have a local origin, the weathering of other MPs and their acquisition of
55 extraneous geosolids and salts suggests that long-range transport is also important. Back-
56 trajectory calculations indicate that regional sources are mainly to the north and west of Ahvaz,
57 but a southerly, maritime source is also possible in late autumn. Although concentrations of
58 MPs in the atmosphere are well below those encountered in indoor air, further studies are
59 required to elucidate their potential ecological impacts.

60

61 **Keywords:** microplastics; atmosphere; transport; fibres; polymers; Ahvaz

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65 **1. Introduction**

66 Microplastics (MPs) are pervasive and ubiquitous environmental contaminants that have
67 received intensive scientific study over the past two decades (Browne et al., 2011; Li et al.,
68 2018; Buks and Kaupenjohann, 2020). Amongst the environmental compartments, the
69 atmosphere has gained the least attention in this respect, despite being an important receptor
70 and transporter of pollutants more generally (Zhang et al., 2020). A variety of polymers and
71 forms or shapes of MP exist in the atmosphere but the particle population appears to be
72 dominated by fibres that are derived from clothing, decorative, automotive, agro-, medical and
73 industrial textiles and fabrics (Cai et al., 2017; Allen et al., 2019; Roblin et al., 2020; Wright
74 et al., 2020). Plastic-based fibres generally co-exist with fibres derived from other artificial and
75 natural (but processed) substances that have similar aerodynamic properties (Dris et al., 2016;
76 Dris et al., 2017; Liu et al., 2019a; Stanton et al., 2019; Constant et al., 2020).

77 Both passive and active sampling approaches have revealed that MPs widely exist in the
78 atmosphere and undergo dry and wet deposition, with their detection in areas remote from
79 population centres, industrial activities or agricultural practices indicating a propensity for
80 long-range transport (~ 1000 km) with air-masses (Bergmann et al., 2019; Brahney et al.,
81 2020). Long-range transport acts as a vector for the direct input of airborne MPs into the oceans
82 (Liu et al., 2019b; Szewc et al., 2021) but evidence also suggests oceans may act as an indirect
83 source of MP to the atmosphere through bubble burst ejection and wave action (Allen et al.,
84 2020).

85 In order to better our understanding of the nature and behaviour of MPs in the atmosphere, we
86 used a high volume air sampler to collect material from the lower atmosphere of an urban arid
87 environment (Ahvaz, Iran). Specifically, we employed a standardised EPA method for the
88 collection of particulate matter (PM₁₀) on sixteen occasions over a four-month period from an

89 urban and industrial location. MPs were determined after sample digestion in H₂O₂ and particle
90 separation by density and were subsequently characterised according to shape-form, size and
91 polymeric construction using established techniques. This information, coupled with back
92 trajectory calculations, was used to gain an insight into the sources, environmental drivers and
93 potential health impacts of airborne MP in the region.

94

95 **2. Material and Methods**

96 *2.1. Study area*

97 The city of Ahvaz lies on the Karun River on the Khuzestan plain (at about 20 m above sea
98 level) in southwest Iran. Ahvaz is an important economic and industrial centre and, with a
99 population of about 1,300,000, is the largest city and capital of Khuzestan province. The city
100 experiences a subtropical hot desert climate, with long hot summers (when temperatures can
101 exceed 50 °C and dust storms and sand storms occur) and cool short winters (when
102 temperatures can be as low as 5 °C). Annual average rainfall is about 230 mm and prevailing
103 winds are from the northwest.

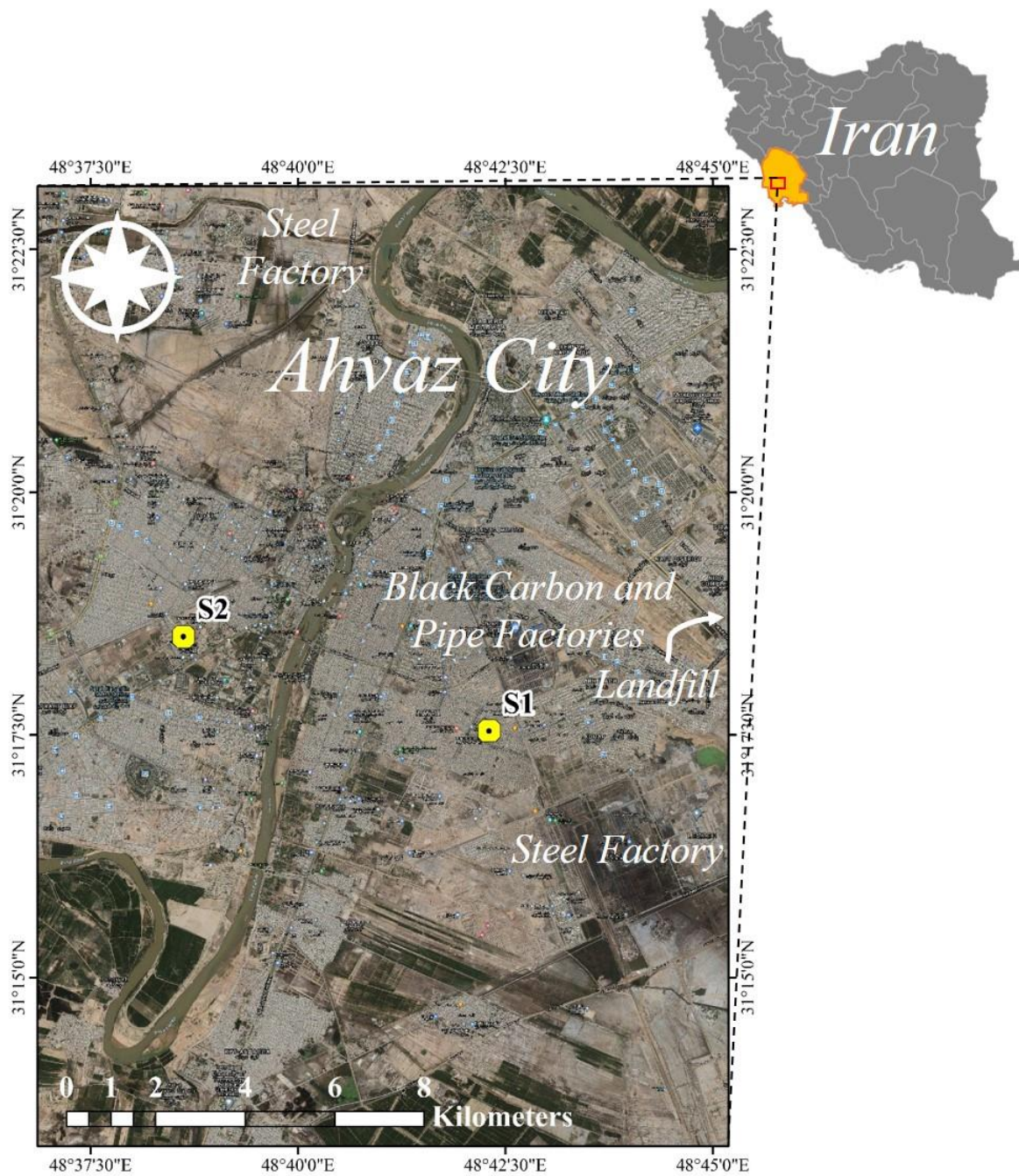
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105 *2.2. Sampling of air-borne particulate matter*

106 A total of 32 suspended particulate matter (PM) samples were collected from two locations on
107 16 occasions free from any precipitation and at 7- to 11-day intervals between summer and
108 winter, 2019. Station 1 (S1; industrial) is to the east of the Karun River and is close to a steel
109 factory, landfill site and carbon black and pipe manufacturers and has a relatively low traffic
110 load; station 2 (S2; urban) is to the west of the river and is located in a more residential and
111 light industrial setting but has a relatively high traffic load (Figure 1).

112 Samples of PM were collected on pre-weighed, 203 x 254 mm rectangular glass-fibre filters
113 (1.6 μm pore size; Whatman G653) using a Tisch high volume air sampler. Here, air is drawn
114 through a size-selective sampling inlet and the filter medium by means of a blower, with
115 particles whose aerodynamic diameters are less than the cut-point of the inlet collected on the
116 filter. We selected a size cutoff of 10 μm (PM10) and, in accordance with US EPA references
117 methods (EPA, 1999), deployed the sampler at a height of 10 m above ground level and with
118 a flow rate of 1.3 m^3 per minute. After 24 h, filters were transferred to glass petri dishes that
119 had been washed with filtered (2 μm), deionised water before being returned to the laboratory
120 for MP extraction and counting.

121



122

123 Figure 1. Suspended particulate matter sampling stations in the city of Ahvaz, Iran

124

125 *2.3. Extraction and counting of microplastics*

126 Filters were stored in a desiccator at 25 °C and for 24 h before being weighed using an
 127 electronic analytical microbalance (LIBROR AEL-40SM, Shimadzu). Each filter was then

128 placed in a glass beaker with filtered, deionized water and the contents shaken for 24 h at 350
129 rpm. Any visible material remaining on the filter was carefully dislodged with a metallic razor
130 and the particle-water suspension subsequently transferred to a clean beaker that was then
131 placed in a sand bath at 80 °C. Before the water had completely dried, residues were mixed
132 with 35 mL of 30% H₂O₂ (Arman Sina, Tehran) for 10 d at room temperature in order to remove
133 organic matter. Residual particulate material was then retrieved by vacuum-filtering the
134 remaining H₂O₂ solution through an S&S filter paper (2 µm pore size). Fifty mL of a saturated
135 solution of ZnCl₂ (Arman Sina, Tehran) and a density of 1.6 to 1.8 g cm³ was added to each
136 filter in a clean beaker and the contents shaken for 5 min at 350 rpm before being allowed to
137 settle for 1 h. The overlying liquid was carefully siphoned off and centrifuged for 3 min at 4000
138 rpm and the supernatant vacuum-filtered onto a new S&S filter. To capture all MPs, the process
139 of density separation, centrifuging and filtering was repeated twice through the same filter.
140 Filters were dried in a metal cabinet at room temperature for a few days before being transferred
141 to individual glass Petri dishes for counting.

142 For the identification of MPs and the exclusion of other materials (including rubbers) derived
143 from the airborne PM samples, binocular microscopy (Carl-Zeiss) was used with commonly
144 employed visual characteristics (e.g. form, opacity, hardness, gloss) and reaction to a hot
145 stainless steel probe (Hidalgo-Ruz et al., 2012; Abbasi et al., 2019). MPs were classified
146 according to colour as white-transparent, yellow-orange, red-pink, blue-green or black-grey,
147 according to shape as fibre, film, fragment or spherule, and, with the aid of the probe and
148 ImageJ software, according to length or primary diameter, L ($L \leq 100 \mu\text{m}$; $100 < L \leq 250 \mu\text{m}$;
149 $250 < L \leq 500 \mu\text{m}$; $500 < L \leq 1000 \mu\text{m}$; $L > 1000 \mu\text{m}$). Based on the optical microscopy
150 results, the topography and elemental composition of selected MP ($n = 24$) recovered from the
151 PM samples were determined through high vacuum scanning electron microscopy/energy-
152 dispersive X-ray microanalysis (SEM/EDX) using a Tescan VEGA 3 microscope (with a

153 resolution of 2 nm at 20 kV) and an Oxford Instruments X-Max 50 silicon drift detector with
154 AZtec and INCA software. Here, samples that had been carefully brushed from the filters were
155 mounted on double-sided adhesive carbon tabs on aluminium SEM stubs. The polymeric
156 construction of 19 MP of a range of shapes, sizes and colours was determined using a micro-
157 Raman spectrometer (LabRAM HR, Horiba, Japan) with a laser of 785 nm and Raman shift of
158 400-1800 cm^{-1} and with acquisition times between 20 and 30 s.

159

160 *2.4. Quality control*

161 In order to prevent plastic contamination during the extraction phase of the air-borne PM
162 samples in the laboratory, all reagents and distilled water were filtered through S&S blue band
163 filters, working surfaces were thoroughly wiped with ethanol, all glassware was cleaned with
164 distilled water and all windows and doors were closed. White cotton laboratory coats, single-
165 use latex gloves and facemasks were worn throughout sample manipulation and processing
166 and, where possible, samples and containers were protected by aluminium foil. Two beakers
167 containing filtered water only were subject to the same procedures as beakers that originally
168 contained sample (glass fibre) filters and filtered water. Analysis of final (S&S) filters arising
169 from this process revealed no detectable MP contamination under the working conditions
170 employed. For replication purposes, three random filters from both stations were recounted for
171 MPs, with results being identical in each case.

172

173 *2.5. Trajectory modelling*

174 The potential source range of MP to the study area was determined from back trajectory
175 frequencies calculated using the National Oceanic and Atmospheric Administration online
176 software, Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT), and Global

177 Forecast System (0.25 degree global) meteorological data. Thus, on each sampling occasion,
178 24-hour backward trajectories were computed from Ahvaz at eight-hour intervals and for the
179 48-h preceding sampling at a height of 500 m above ground level and a resolution of 1 degree.
180 Integrated trajectory data were then used to plot percentage frequency distributions. This
181 approach is commonly used to infer airborne MP sources (Brahney et al., 2020; González-
182 Pleiter et al., 2021), although the model itself does not account for particulate transport or
183 particle deposition unless appropriate parameters are included.

184

185 **3. Results**

186 The mass concentrations of PM (with a maximum aerodynamic diameter of 10 μm and per m^3
187 of air) are shown in Table 1 for both stations and on each occasion sampled. Mean, minimum
188 and maximum concentrations are similar at S1 (68.46, 35.34 and 98.34 $\mu\text{g m}^{-3}$, respectively)
189 and S2 (63.62, 39.64 and 94.64 $\mu\text{g m}^{-3}$, respectively) and, overall, there was relatively little
190 variation amongst the measurements (relative standard deviation $\sim 25\%$; $n = 32$). Moreover,
191 there was no clear relationship between PM concentration and date, mean air temperature or
192 mean wind speed for either station and no significant (linear) relationship ($p > 0.05$) between
193 concentrations at the different sites determined on the same dates.

194 The number of MPs recovered from each filter deployed for a 24-h period was more variable,
195 ranging from none detected (on five occasions) to 31 at S1 and none detected (on two
196 occasions) to 28 at S2. Where MPs were detected, concentrations on a number basis ranged
197 from about 0.002 to 0.017 m^{-3} and from 23 to 341 per g of PM at S1 and about 0.002 to 0.015
198 m^{-3} and from 34 to 162 per g of PM at S2, with no significant differences ($p > 0.05$ according
199 to Kruskal-Wallis tests) in the means of either measure between the two stations.

200

201

202

203 Table 1: Mean daily air temperatures and wind speeds, and concentrations of PM and the
204 number and concentrations of MPs (per m³ of air and per g of PM) at stations S1 and S2
205 determined over sixteen 24-h periods in 2019 (nd = none detected).

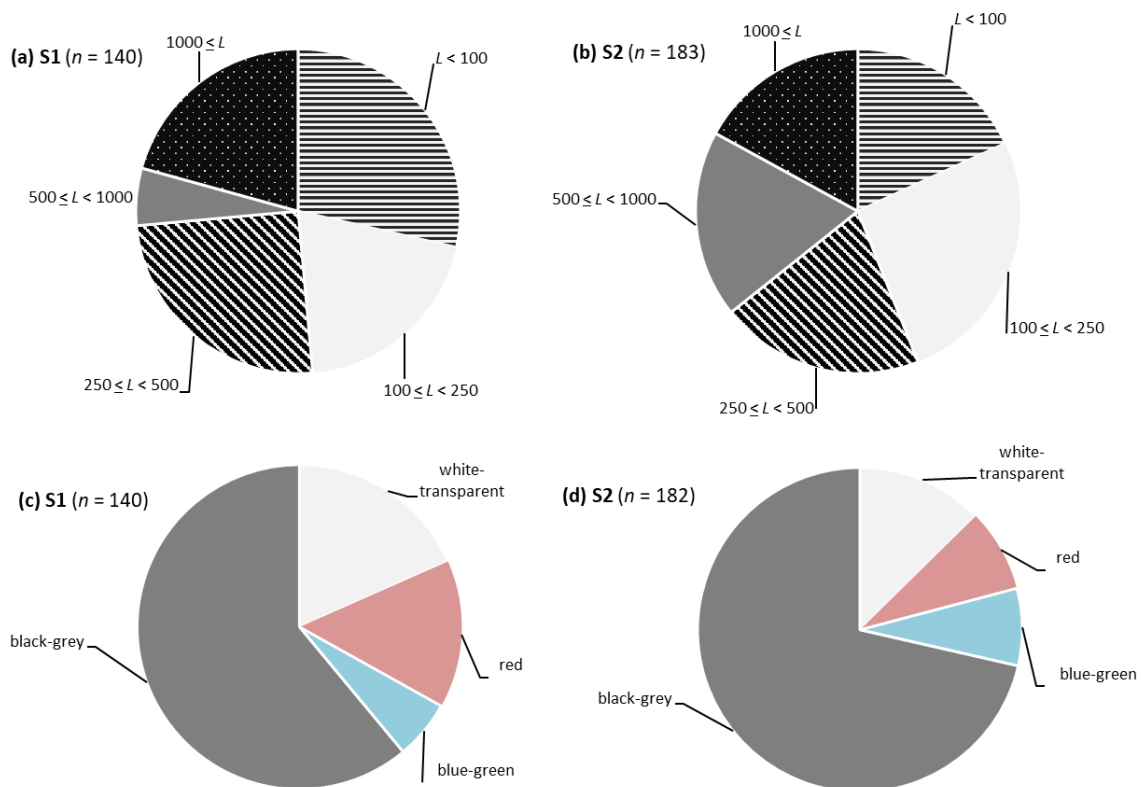
Date	Temp., °C	Wind speed, km h ⁻¹	S1			S2				
			[PM], µg m ⁻³	MP, n	[MP], n m ⁻³	[MP], n g ⁻¹	[PM], µg m ⁻³	MP, n	[MP], n m ⁻³	[MP], n g ⁻¹
28/08/2019	40	6.4	74.59	13	0.0069	93	42.36	8	0.0043	101
04/09/2019	39	30.5	66.34	15	0.0080	121	86.29	20	0.0107	124
15/09/2019	37	12.9	57.61	17	0.0091	158	51.39	12	0.0064	125
22/09/2019	33	8.0	48.57	31	0.0166	341	62.46	16	0.0085	137
29/09/2019	33	20.9	94.67	13	0.0069	73	53.67	8	0.0043	80
06/10/2019	30	11.3	98.34	12	0.0064	65	72.64	16	0.0085	118
31/10/2019	28	12.9	78.64	nd	nd	nd	53.64	9	0.0048	90
20/09/2019	25	17.7	72.38	9	0.0048	66	57.67	16	0.0085	148
28/10/2019	20	12.9	94.67	4	0.0021	23	83.64	12	0.0064	77
06/11/2019	20	11.3	67.69	nd	nd	nd	39.64	5	0.0027	67
31/11/2019	20	11.3	61.67	nd	nd	nd	47.59	3	0.0016	34
21/11/2019	18	6.4	35.34	9	0.0048	136	51.67	13	0.0069	134
29/11/2019	16	8.0	67.12	8	0.0043	64	55.84	nd	nd	nd
07/12/2019	16	22.5	54.63	nd	nd	nd	94.64	16	0.0085	90
14/12/2019	16	9.6	65.59	nd	nd	nd	92.46	28	0.0150	162
22/12/2019	15	4.8	57.48	9	0.0048	84	72.34	nd	nd	nd

206

207

208 In total, 322 MPs were identified amongst the PM samples, with binocular microscopy
209 indicating that all particles were of a fibrous nature. The sizes and colours of the MPs are
210 summarised in Figure 2 for both stations. Thus, at S1, each size range comprised about 20-30%
211 of the particle population with the exception of 500 to 1000 µm (about 5%), while at S2 all size
212 ranges contributed roughly equally to the population. Note that the MPs identified by
213 microscopy were larger than the inlet size of the air sampler (PM10) reflecting aerodynamic
214 properties of MPs that are very different to those of dust particulates. Regarding colour, black-
215 grey was dominant (about 60% and 70% of MP at S1 and S2, respectively), with percentage
216 contributions from remaining colours < 20 and yellow-orange fibres entirely absent. Analysis
217 of 19 MPs by Raman spectrometry revealed that nine were constructed of polyethylene
218 terephthalate (PET), five were polypropylene, three were nylon and two were polystyrene.

219



221

222

Figure 2: Size (in μm) and colour distribution of MPs at the two stations.

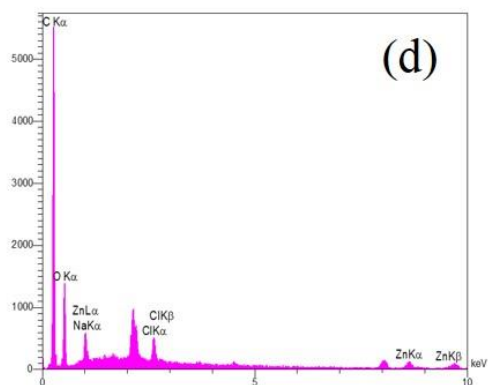
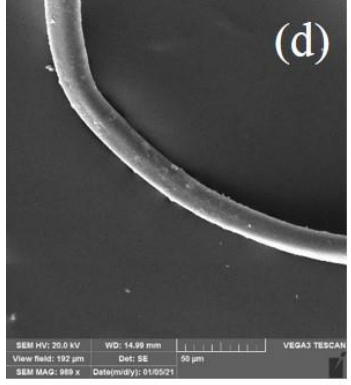
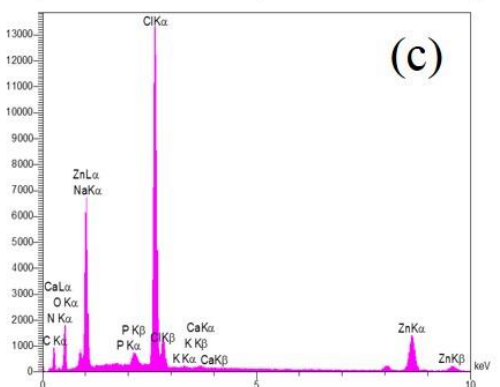
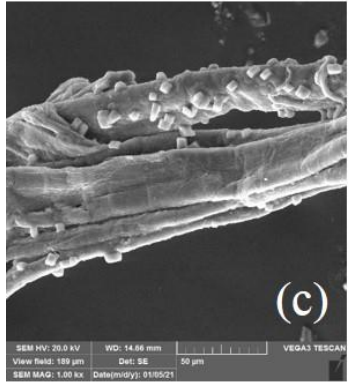
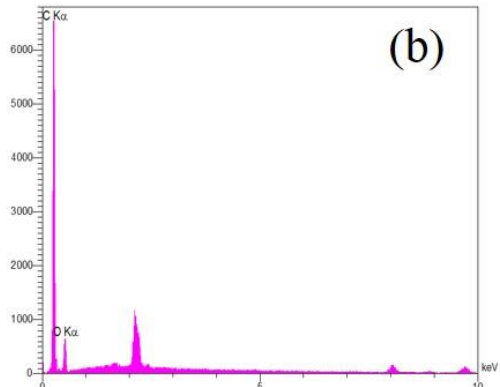
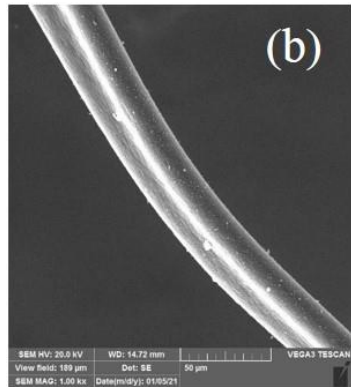
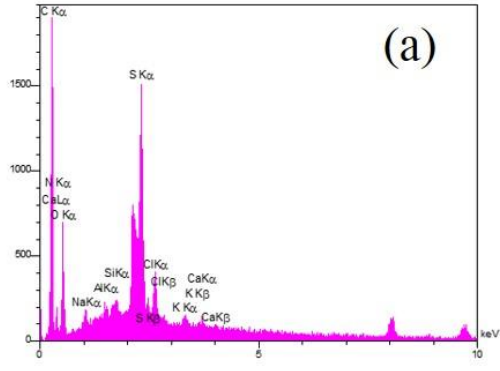
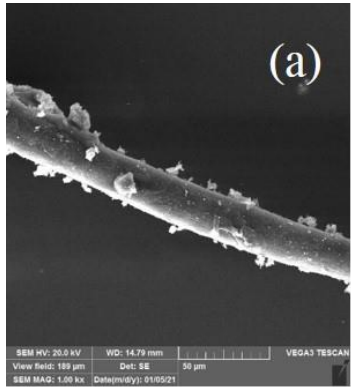
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224 Imaging of selected samples by SEM, exemplified in Figure 3, revealed that most MP consisted
 225 of single straight, curved or coiled threads of 15 to 35 μm in diameter that were transversally
 226 round, many of which were smooth and clean. However, occasional samples consisted of
 227 multiple threads that were intertwined, entangled or bundled and that tended to exhibit greater
 228 degrees of mechanical and chemical weathering (pits, grooves, flaking). Some fibres appeared
 229 to be contaminated by extraneous solids, with EDX analysis confirming the presence of
 230 inorganic and organic geogenic material (e.g., Al, Ca, Na, Si) and residual salts arising from
 231 sample separation and preparation.

232

233

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235

236 Figure 3: SEM images and EDX spectra for four selected samples. (a) A blue PET fibre
237 showing contamination by extraneous PM containing S, Na, Ca, K, Al and Si, (b) a red Nylon
238 fibre, (c) intertwined white PET fibres with evidence of contamination by extraneous PM and
239 residual ZnCl₂ arising from sample separation and (d) a blue PET fibre with evidence of
240 contamination by NaCl.

241

242 **4. Discussion**

243 Despite a strong seasonality across the sampling period (and in particular, a significant drop in
244 temperature from August to December), airborne concentrations of PM with a maximum
245 aerodynamic diameter of 10 µm were rather constant at both stations in Ahvaz. The temporal
246 distribution of MPs, however, was more heterogeneous, with no clear seasonal modification of
247 the type, size or abundance at either station, and no clear difference in these characteristics
248 between the two stations. The dominance of fibres and plastics mainly constructed of PET (a
249 polyester), nylon (a polyamide) and polypropylene are consistent with the few previous studies
250 that have actively sampled outdoor air and characterised suspended MPs (Dris et al., 2017; Liu
251 et al., 2019a; Liu et al., 2019b; González-Pleiter et al., 2021) and confirm the ubiquity of such
252 particulates in the atmosphere. However, the concentrations of MPs on a number basis that we
253 observe (always < 0.02 m⁻³ and an overall median where MPs were detected of 0.0065 m⁻³) are
254 low compared with these studies.

255 Thus, Dris et al. (2017) observed concentrations of fibres in suburban Paris ranging from 0.3
256 to 1.5 m⁻³ (median 0.9 m⁻³), although only one third of the fibres were plastic- (petroleum-)
257 based, and in Asaluyeh County, Iran, Abbasi et al. (2019) found concentrations of MPs ranging
258 from 0.3 to 1.1 m⁻³ (mean 1 m⁻³). In different municipal districts of Shanghai, Liu et al. (2019a)
259 obtained MP concentrations ranging from none detected to 4.2 m⁻³ (mean 1.4 m⁻³), with higher
260 concentrations than in Paris attributed to a greater population density and more intense
261 industrial activities, despite a number of air cleaning activities conducted in the city. Liu and
262 co-workers extended the study into the western Pacific Ocean and obtained concentrations

263 ranging from none detected to 1.4 m^{-3} , with a median of 0.01 m^{-3} (Liu et al., 2019b). One reason
264 for the lower concentrations reported in the present study is that we based our sampling
265 approach on a high volume EPA method for capturing PM₁₀ (EPA, 1999). This employs an
266 inlet cutoff equivalent to an aerodynamic diameter of $10 \text{ }\mu\text{m}$, or a diameter of a unit density
267 sphere having the same terminal settling velocity as the particle in question, and captures
268 particles that, in theory, have the greatest propensity to be inhaled through the human
269 respiratory system. This approach may also explain why we did not detect other shapes of MP
270 (e.g., spheres, granules or fragments) on the filters.

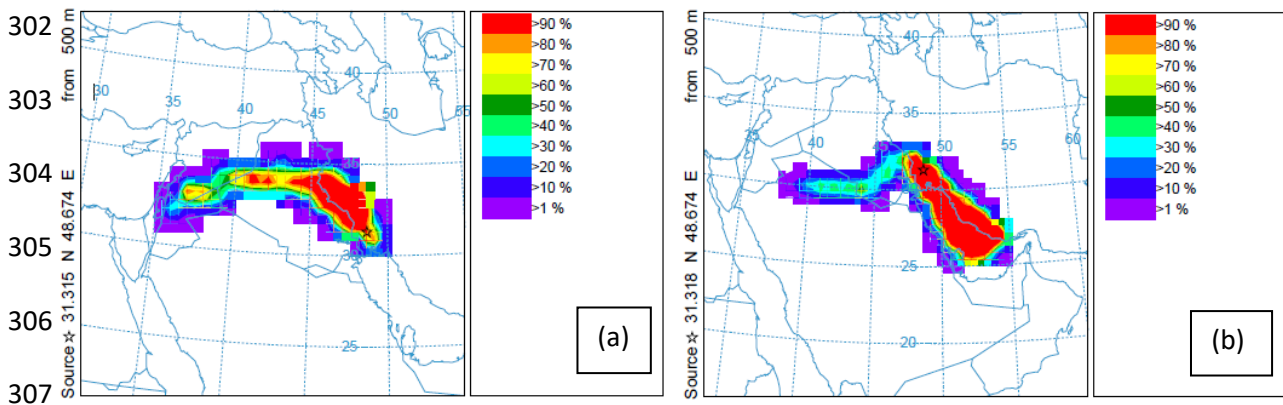
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272 Fibrous MPs are likely to be generated from synthetic textiles and fabrics used in clothing,
273 upholstered furnishings and carpets, industry and automobiles (Dris et al., 2017; Wright et al.,
274 2020; Zhang et al., 2020), with the dominant polymer types identified in the present study
275 (PET, polyamide, polypropylene) consistent with their importance in these sectors (Urdogan,
276 2012; Turner, 2019) and in indoor air (Dris et al., 2017). The proximity of the stations in Ahvaz
277 to residential and industrial areas suggests that local sources of fibrous MPs might be important,
278 with those fibres exhibiting little evidence of weathering presumably derived recently.
279 However, the detection of fibrous MPs in locations remote from any anthropogenic sources,
280 including the Alps, Pyrenees, Arctic and various protected areas of the US (Allen et al., 2019;
281 Bergmann et al., 2019; Brahney et al., 2020), as well as above the planetary boundary layer
282 (González-Pleiter et al., 2021), suggests that long-range transport with regional air masses may
283 also be important. Transport of domestic, automotive, industrial and agricultural fibres over
284 long distances, coupled with regular interactions with surface (ground) materials and features,
285 may account for the mechanical and chemical weathering observed on many fibres sampled in
286 the present study.

287

288 Results of our trajectory modelling using HYSPLIT are exemplified in Figure 4. Within the
 289 constraints and limitations of this approach (and mainly the assumption that MPs are carried in
 290 the same direction and with the same velocity as air itself and without deposition and re-
 291 entrainment), the results indicate the broad regions from which MP may have been transported
 292 into Ahvaz in the short-term. Thus, on most occasions considered, trajectories spread
 293 immediately to the north and northwest, with 90% frequencies extending to 300 to 600 km.
 294 Towards late autumn, however, a southerly component was sometimes observed with the
 295 highest frequencies located over the Persian Gulf. One of the fibres examined by SEM-EDX
 296 that was sampled when trajectories were southerly revealed the presence of Na and Cl without
 297 any other geogenic signature (Figure 3d), consistent with residual NaCl from a maritime
 298 source. Overall, the trajectories embrace a range of land uses, agricultural practices, industries,
 299 geomorphologies and demographics which may, at least partly, account for the heterogeneity
 300 of the fibrous MPs observed in Ahvaz in the present study.

301



308 Figure 4: Twenty-four-hour back-trajectory frequency distributions calculated for Ahvaz
 309 (located with a star) on (a) 4/9/2019 and (b) 7/12/19.

310

311 Regarding human exposure, and assuming that on average 15 m³ of air is inhaled daily and that
 312 ten hours per day are spent outdoors, our data suggest that up to about 0.1 fibrous MP whose

313 aerodynamic diameters, by operational definition, are less than 10 μm are consumed over a 24-
314 hour period. This compares with the consumption of up to about 180 fibrous MP when exposed
315 to indoor air containing 20 MP m^{-3} (determined by Dris et al., 2017) assuming that fourteen
316 hours per day are spent inside. Although this comparison is subject to errors and uncertainties
317 associated with the precise aerodynamic dimensions of the collection systems employed, the
318 lower size limit of MP detection, the ability of the respiratory system to filter out fibres, and
319 the habits of individuals and the conditions and styles of their homes, it is clear that MP
320 exposure to the general public is far more important in the indoor setting than the outdoor
321 environment. Nevertheless, the more general impacts of airborne and deposited fibrous MPs
322 on terrestrial flora, fauna and ecosystems are largely unknown and require further study (He et
323 al., 2020; Liu et al., 2020).

324

325 **5. Conclusions**

326 Airborne MPs collected with PM10 from urban and residential locations in Ahvaz over an
327 extended, seasonal period, were fibrous in nature. However, abundance and characteristics
328 displayed no clear temporal trends or differences between the two locations, with overall
329 maximum and median concentrations of 0.017 and 0.0065 m^{-3} , respectively. Fibres were
330 dominated by PET, polyamide and polypropylene, reflecting their use in synthetic textiles and
331 fabrics, and displayed varying degrees of weathering and contamination by extraneous
332 geogenic particles. The latter observation suggests both local and more distal origins of MPs,
333 with HYSPLIT back trajectories indicating regional sources to the north and west of Ahvaz
334 and a southerly, maritime source in late autumn. As components of PM10, further research is
335 required into any possible impacts of fibrous MPs on human health and wildlife.

336

337

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341

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