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1 *Atmospheric transport of microplastics during a dust storm*

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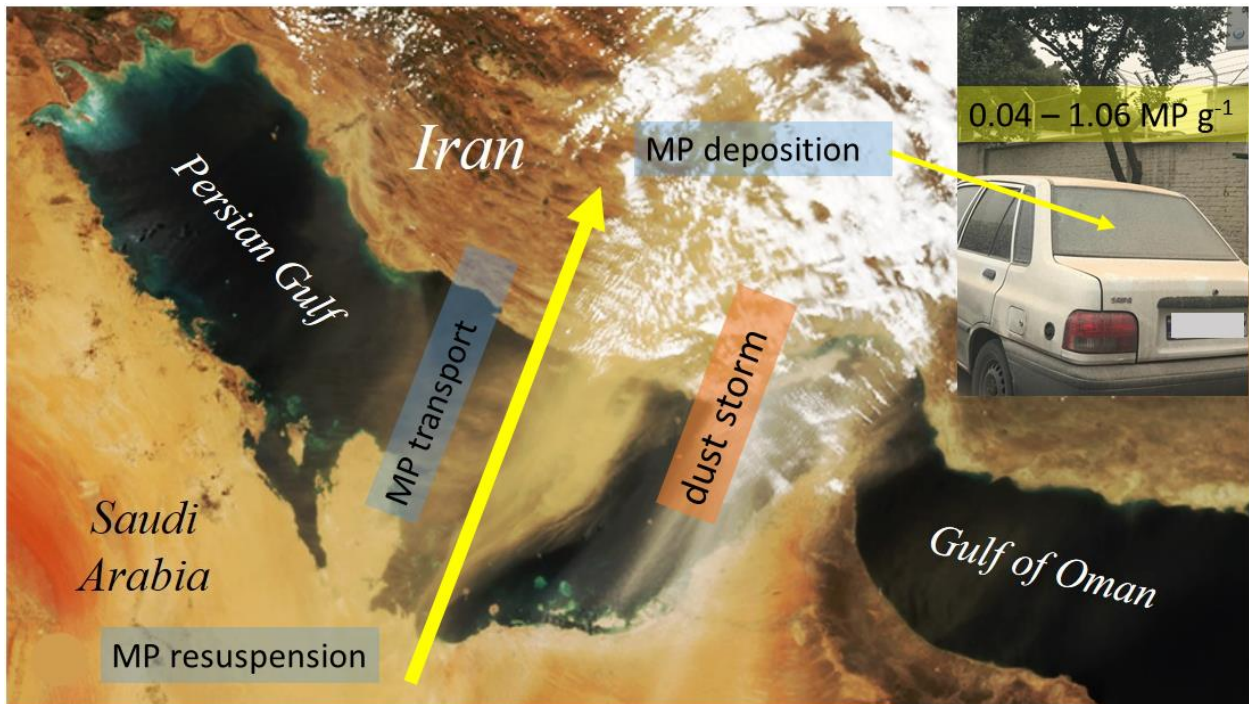
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31

32 Graphical Abstract



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36

37 **Abstract**

38 Dust storms are common events in arid and semi-arid regions that have a wide range of impacts
39 on the environment and human health. This study addresses the presence, characteristics and
40 potential sources of microplastics (MPs) in such events by analysing MPs deposited with **dust**
41 **particles** in the metropolis of Shiraz, southwest Iran, following an intense storm in May 2018. At
42 22 locations throughout the city, MP concentrations on a number basis ranged from 0.04 to 1.06
43 per g of dust (median = 0.31 MP g⁻¹). Particles were mainly fibrous, with a mean diameter of about
44 20 µm and > 50% under 100 µm in length, and polymer makeup was dominated by **nylon**,
45 polypropylene and polyethylene terephthalate. Examination of selected MPs by scanning electron
46 microscopy revealed varying degrees of weathering and contamination by extraneous geogenic
47 particles amongst the samples. Using published MP concentrations in urban dusts and remote, arid
48 soils, we estimate that between about 0.1 and 5% of MPs deposited by the dust storm are derived
49 from local sources within the metropolis, with the remainder arising from more distant sources.
50 HYSPLIT modelling, satellite imagery and published geochemical signatures of regional **dust**
51 **particles** suggest that the deserts of Saudi Arabia constitute the principal distal **and transboundary**
52 source. Dust storms may represent a significant means by which MPs are transported and
53 redistributed in arid and semi-arid environments and an important source of MPs to the oceans.

54

55 **Keywords:** Microfibres; Weathering; Deposition; Source; Flux; Iran

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60 **1. Introduction**

61 Dust storms are intense suspensions of geogenic silt- and clay-sized particulates that may last for
62 several hours to several days. These events result from strong and turbulent winds acting on loose,
63 sparsely vegetated soils and lithological units in arid and semi-arid regions, and in particular in
64 inland drainage basins, and have the propensity to transport airborne particles over long distances
65 (Tan et al., 2012; Srivastava et al., 2018; van der Does et al., 2018; Rashki et al., 2021). Dust
66 storms have many and varied impacts on weather, climate and the environment. For example, high
67 dust loadings may affect air temperature, cloud formation and convectional activity (including
68 hurricane intensity) and are believed to play a major role in the delivery of iron and other nutrients
69 to the oceans (Goudie, 2009). Dust storms also have significant adverse impacts on agriculture,
70 urban infrastructure, solar power production, the economy, and human health and safety (Rashki
71 et al., 2021). Regarding the latter, high loadings of suspended geogenic particles are directly
72 responsible for transport accidents and respiratory complaints, cardiovascular diseases and other
73 illnesses (Pauley et al., 1996; Tam et al., 2012), while the presence of associated materials or
74 chemicals, like bioaerosols, heavy metals and radionuclides, may pose additional allergenic or
75 chronic health risks (Ogorodnikov, 2011; Behrooz et al., 2020; Soleimani et al., 2020).

76 In the recent literature, the role of the atmosphere in the long-range transportation of microplastics
77 (MPs) has been highlighted (Allen et al., 2019; Liu et al., 2020; Roblin et al., 2020). Thus, MPs,
78 and in particular fibrous MPs that have relatively high aspect ratios (and surface area-to-volume
79 ratios) and low settling velocities (Brahney et al., 2020; Wright et al., 2020), can be transported
80 100s or 1000s of km from their point of origin before undergoing dry or wet deposition (Liu et al.,
81 2019; Abbasi and Turner, 2021; González-Pleiter et al., 2021). Because of their small size and
82 persistence, MPs in the atmosphere are a concern from a human health perspective (Prata, 2018),

83 while their deposition in soils, lakes and the ocean represents a means by which MP may be moved
84 between ecosystems and exert impacts on a wide range of organisms (Arias-Andres et al., 2019;
85 Sobhani et al., 2021). With dust storms capable of shifting significant quantities of loose soils, and
86 MPs known to be dispersed amongst soils remote from any urban, industrial and agricultural
87 sources (Feng et al., 2020; Abbasi et al., 2021a), it is hypothesized that storm events may act as a
88 vehicle for transporting considerable quantities of fine, resuspendable MP. Accordingly, the
89 present study involves the opportunistic sampling of dust deposited throughout the metropolis of
90 Shiraz, Iran, immediately after a particularly intense dust storm in May 2018. MPs were isolated
91 from the deposited dust particles, and quantified and characterized by established techniques in
92 order to gain an insight into the significance of dust storms in Iran, and more generally, to the
93 global atmospheric dispersion and redistribution of plastics.

94

95 **2. Methods**

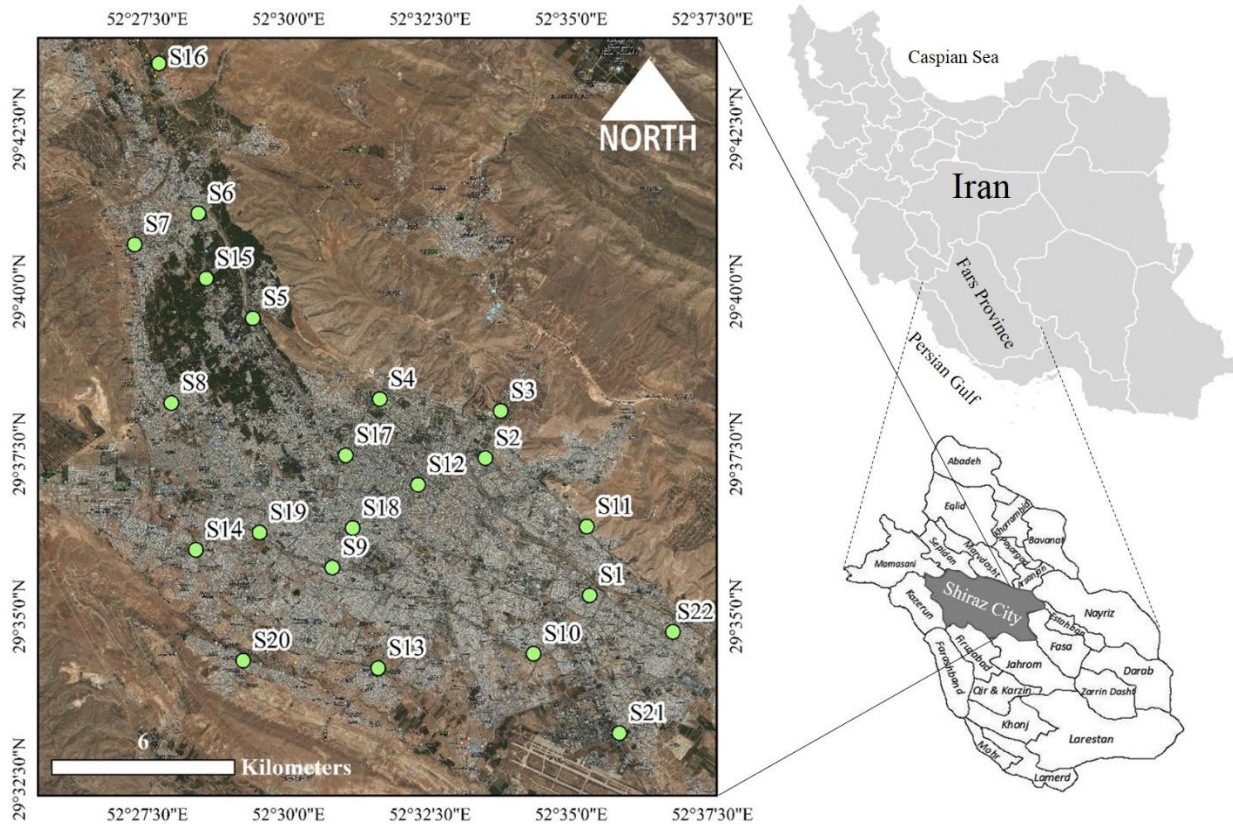
96 ***2.1. Study area and sample collection***

97 Shiraz is the largest city of Fars province and southwestern Iran, with a population of about 1.6
98 million contained within an area of 240 km² and lying about 1500 m above sea level. The region
99 is arid in summer and rainy and mild in winter, with an annual average temperature and rainfall of
100 18°C and 337 mm, respectively, and predominantly southeasterly and easterly winds. The air
101 quality of Shiraz has declined over recent years because of the rapid growth in population, traffic
102 volume and industrialization (Gharehchahi et al., 2013), coupled with an increased incidence of
103 dust storms (Alizadeh-Choobari et al., 2015). The frequency of dust “events” in Shiraz appears to
104 be between 1 and 3% (Alizadeh-Choobari et al., 2015) but on May 13th 2018, a particularly intense

105 dust storm occurred in the region that involved the **transboundary** transportation of geogenic
106 material originating in Saudi Arabia across the Persian Gulf (Abbasi et al., 2021b).

107 Settled **dust particles** from the storm were collected opportunistically from parked cars, an
108 approach adopted by Bergmann et al. (2019) for the sampling of MPs in fresh European snow.
109 Twenty-two locations (**encompassing urban, residential and commercial areas**) within different
110 municipal sectors of Shiraz (Figure 1 and Table 1) were visited within six hours after the dust
111 **storm** by three operators, and five to ten cars at each location were selected from bays with
112 restricted (i.e., not long-term) parking. Sampling involved the careful but rapid retrieval of material
113 from the central regions (about 40 x 40 cm) of windscreens or back windows using a pre-cleaned
114 **wooden brush with horsehair bristles** and a stainless steel dustpan by an operator wearing cotton
115 clothing. Composite samples from each location were stored in 300 mL glass jars and the brush
116 **and pan were washed several times with filtered water between sampling locations**. The general
117 atmospheric conditions in Shiraz at this time of year require car windows to be regularly cleaned
118 while driving and we assume, therefore, that the majority of material collected from the windows
119 arose largely from the storm and not from more general, ambient urban deposition.

120



121

122

123

Figure 1: Sampling locations within the metropolis of Shiraz, southwest Iran.

124

125 **2.2. Sample treatment and microplastic extraction**

126 Dust samples were transferred to individual, 600-mL glass beakers using a stainless steel spoon

127 before being dried for 24 h at 25°C. Dried samples were then sieved through a 5-mm stainless steel

128 mesh, with 50 g of each weighed into individual clean beakers on a Libror AEL-40SM balance

129 (Shimadzu, Kyoto). The contents of each beaker were oxidized with 200-300 mL of 35% H₂O₂

130 (Arman Sina, Tehran) at room temperature until bubble formation ceased. Remaining particulate

131 matter was washed with filtered, deionized water through a 150 mm diameter S&S filter paper

132 (blue band, grade 589/3, 2 μm pore size) housed in a glass-ceramic vacuum filtration kit before

133 being dried in a sand bath at 60°C for 2 h.

134 To isolate MPs, each dried, digested sample was transferred to a saturated 300 mL solution of
135 ZnCl₂ (Arman Sina, Tehran; density 1.6 – 1.8 g cm⁻³) in a series of clean glass beakers, and the
136 decanted contents were subsequently centrifuged at 4000 rpm before supernatants were vacuum-
137 filtered through S&S filter papers. This process was repeated twice, with resulting filters air-dried
138 for 48 h at 25 °C under laminar flow and transferred to glass Petri dishes for physical and chemical
139 characterization.

140 *2.3. Quality assurance and control*

141 Appropriate measures were taken to minimize MP contamination in the laboratory. Thus, benches
142 were cleaned with ethanol using cotton cloths, laboratory clothing was cotton-based and all
143 reagents and solutions were vacuum-filtered through S&S blue band filters (< 2 µm) before being
144 used. All glassware was washed with phosphate-free soap, double rinsed with filtered (< 2 µm)
145 water and soaked in 10% Merck Suprapur HNO₃ for 24 h before being rinsed twice with double-
146 distilled water and air-dried at room temperature in a clean room. Where possible, containers were
147 protected by covering or wrapping in aluminium foil. Controls, consisting of empty beakers that
148 were processed as above, revealed no detectable airborne MP contamination throughout sample
149 processing and storage.

150

151 *2.4. Microplastic identification*

152 MPs on filters were identified and quantified according to thickness and cross sectional properties,
153 shininess, hardness, surface structure and reaction to a hot, 250 µm stainless steel needle under a
154 binocular microscope (Carl-Zeiss) at up to 200 x magnification and with the aid of ImageJ
155 software. Particle size, with a lower limit of about 20 to 50 µm depending on shape and colour,

156 was estimated along the length of the longest axis, L ($L \leq 100 \mu\text{m}$, $100 < L \leq 250 \mu\text{m}$, $250 \leq L <$
157 $500 \mu\text{m}$, $500 \leq L < 1000 \mu\text{m}$, $L \geq 1000 \mu\text{m}$), and colour was grouped as black-grey, yellow-orange,
158 white-transparent, red-pink or blue-green. Shape was classified as film, fragment, spherule-granule
159 or fibre, with the latter defined as having a length to diameter ratio of at least three and diameter
160 estimated to the nearest $5 \mu\text{m}$ with the aid of TCapture software.

161 *The polymeric composition of a selection of MPs from different locations and of different colours,*
162 *sizes and shapes ($n = 39$) was determined using a micro-Raman spectrometer (LabRAM HR,*
163 *Horiba, Japan) with a laser of 785 nm, a Raman shift of 400-1800 cm^{-1} and acquisition times*
164 *between 20 and 30 s. Surface morphology was determined on 21 of these samples, after they had*
165 *been mounted on microscope slides and gold-coated, using a high vacuum scanning electron*
166 *microscope (SEM; TESCAN Vega 3, Czech Republic) operated with a resolution of 2 nm at 20*
167 *kV and equipped with an energy-dispersive X-ray microanalyzer (EDX).*

168

169 *2.5. Trajectory calculations*

170 The origins of air masses and potential source range of material from the dust storm was evaluated
171 from 48-h back trajectories for 13th May 2018, calculated using the National Oceanic and
172 Atmospheric Administration online software, Hybrid Single Particle Lagrangian Integrated
173 Trajectory (HYSPLIT) v4, and Global Forecast System (0.25 degree global) meteorological data.
174 Trajectories were calculated at six-hour intervals at a height of 500 m above ground level and a
175 resolution of 1 degree, and were integrated as frequency distributions.

176

177 **3. Results and Discussion**

178 *3.1. Distribution and characteristics of microplastics*

179 The number and distribution (by size and shape) of the MP identified in the present study are
180 shown for each location sampled in Table 1. Overall, 485 MP were recorded that were dominated
181 by fibres ($n = 448$ or $\sim 92\%$). Small contributions arose from films ($n = 35$) and fragments ($n = 2$)
182 but more regular spherules-granules were never detected. Regarding MP colour, $> 50\%$ were
183 white-transparent, 23% were red-pink, 10% were black-grey or yellow-orange, and $< 5\%$ were
184 blue-green; non-fibrous MP were dominated ($\sim 90\%$) by white-transparent films. The total number
185 of MP at each location ranged from 2 to 53, with concentrations on a number basis ranging from
186 0.04 to 1.06 MP per g of dust. Overall, mean and median concentrations were 0.44 and 0.31 MP
187 g^{-1} , respectively, and 25th and 75th percentiles were 0.21 and 0.65 MP g^{-1} , respectively.

188 Fibres were single straight, curled or coiled strands or, occasionally, multiple, intertwined strands,
189 and diameters ranged from about 10 to 40 μm and averaged 18.7 μm . Over 60% of fibres were
190 encountered in the smallest length category considered ($\leq 100 \mu\text{m}$), with a similar distribution
191 among size categories up to 1000 μm (10 to 15%) but $< 0.5\%$ of fibres present above 1000 μm .

192 The percentage in the finest fraction is subject to some uncertainty because of the existence of MPs
193 below our size detection limit and the possibility that some larger fibres may fragment into smaller
194 particles during centrifugation. Nevertheless, the percentage of fibres in this fraction is larger than
195 that reported for deposited dust particles sampled in Shiraz throughout the year (average $\sim 30\%$)
196 that had been processed and identified using the same methodology (Abbasi and Turner, 2021).

197 Based on a range of aspect ratios (β) from 3 to 100, diameters (d) as above and densities (ρ) for
198 the polymers shown in Figure 2 (from 1.0 to 1.4 g cm^{-3}), we estimate aerodynamic equivalent
199 diameters (d_a) from the following equation (Wright et al., 2020):

$$200 \quad d_a = (\rho \ln 2 \beta)^{1/2} d \quad (1)$$

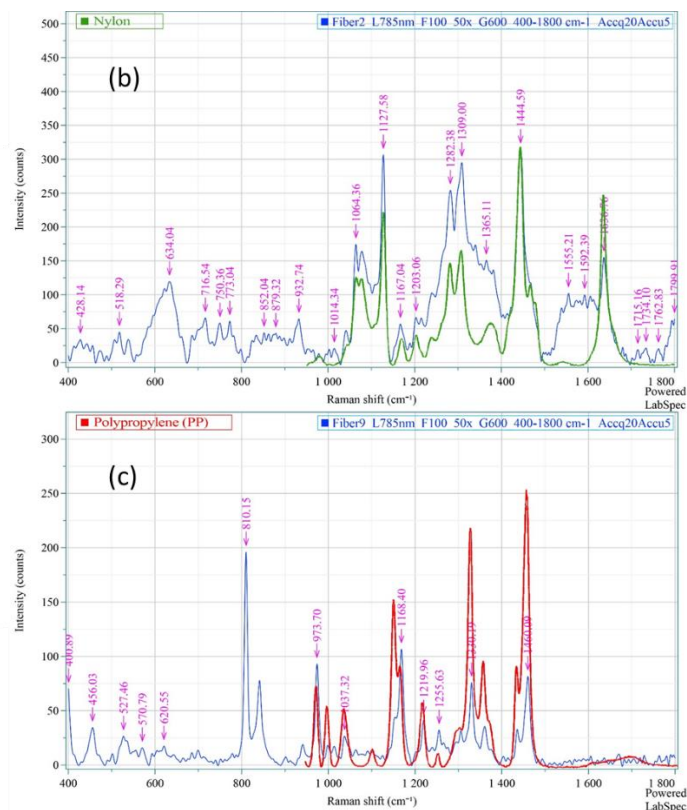
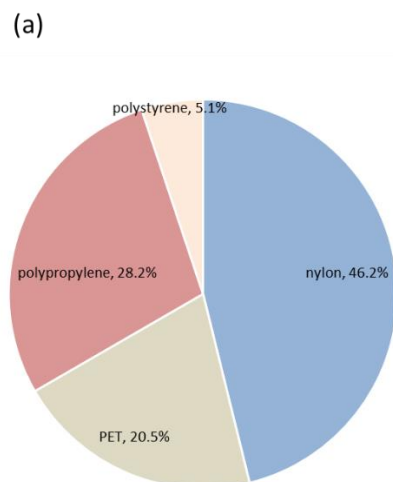
201 to range from about 13 to 130 μm for the fibres detected in the present study.

202 **Table 1: Location of each sampling station** in Shiraz (see Figure 1), along with a summary of the
 203 MP distribution by size and shape. Fibres are categorised according to length, L , but other
 204 (remaining) MPs are not classified by shape or size. Concentration represents the number of MP
 205 per g of dust.

Sample location	UTM coordinates		MP fibres (L , μm)					Other MPs		
	X	Y	< 100	100 \leq L <250	250 \leq L <500	500 \leq L <1000	\geq 1000	All sizes	Total	Concentration, MP g ⁻¹
1	653872	3274271	28	0	0	0	2	0	30	0.60
2	650842	3278127	22	8	1	5	0	1	37	0.74
3	651261	3279474	10	3	10	4	0	0	27	0.54
4	647803	3279769	10	0	0	0	0	0	10	0.20
5	644147	3282014	0	0	0	35	0	3	38	0.76
6	642555	3284973	11	2	0	0	0	2	15	0.30
7	640747	3284072	13	0	0	0	0	0	13	0.26
8	641853	3279579	28	17	0	0	0	2	47	0.94
9	646509	3274962	9	3	0	0	0	0	12	0.24
10	652295	3272590	2	0	0	0	0	0	2	0.04
11	653768	3276225	9	0	0	0	0	0	9	0.18
12	648930	3277346	8	0	0	0	0	0	8	0.16
13	647860	3272117	3	2	4	0	0	3	12	0.24
14	642604	3275416	5	0	11	0	0	0	16	0.32
15	642800	3283128	12	0	28	1	0	6	47	0.94
16	641370	3289215	11	0	0	0	0	0	11	0.22
17	646854	3278154	7	0	0	0	0	0	7	0.14
18	647076	3276095	0	2	13	0	0	8	23	0.46
19	644418	3275928	23	0	0	0	0	10	33	0.66
20	643999	3272283	50	3	0	0	0	0	53	1.06
21	654777	3270363	5	0	0	0	0	0	5	0.10
22	656267	3273264	15	13	0	0	0	2	30	0.60
total			281	53	67	45	2	37	485	
mean			12.8	2.4	3.0	2.0	0.1	1.7	22.0	0.44
min			0	0	0	0	0	0	2	0.04
max			50	17	28	35	2	10	53	1.06

207 The distribution of selected MPs ($n = 39$) from various locations by polymer type is shown in
 208 Figure 2, along with examples of Raman spectra for two fibres. About one half of the samples
 209 were constructed of nylon, with decreasing contributions from polypropylene, polyethylene
 210 terephthalate and polystyrene. Fibres ($n = 31$) were represented by all polymer types detected and
 211 reflect the nature of plastics used in textiles and fabrics (Henry et al., 2019), but films ($n = 6$) were
 212 constructed of only nylon and polypropylene and fragments ($n = 2$) were constructed of nylon.

213



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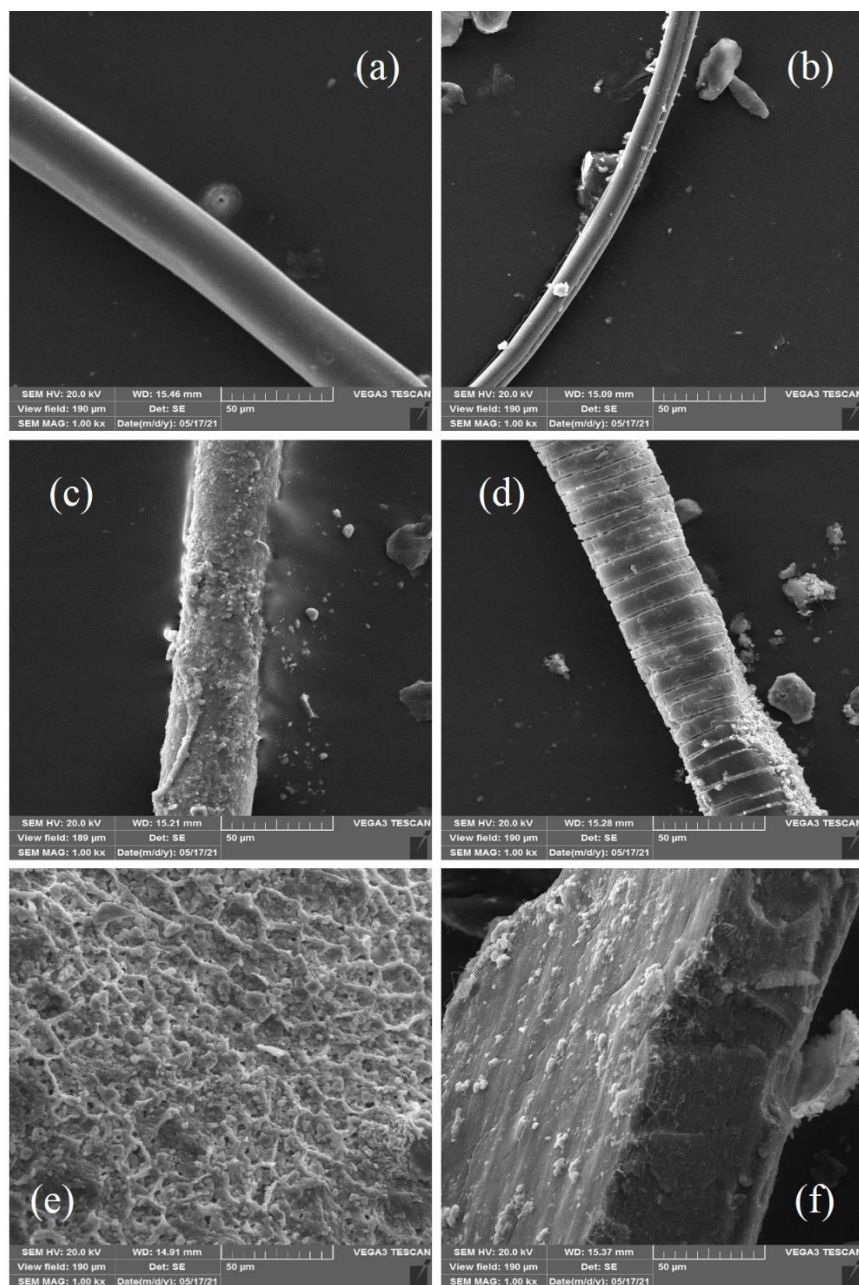
216 **Figure 2:** (a) Relative abundance of 39 MPs by polymer type (PET = polyethylene
 217 terephthalate), and Raman spectra for (b) a nylon fibre and (c) a polypropylene fibre.

218

219 SEM images of selected fibres and films are illustrated in Figure 3. Fibres are uniform in diameter,
 220 with the scale bars confirming that sample diameters ranged from about 10 to 40 μm . The images
 221 suggest varying degrees of weathering and contamination by adherent mineral particles, with EDX
 222 spectra of the latter (and in particular Al, Ca, Mg, Fe, Si and Ti) consistent with the geochemical
 223 signature of soils and lithological units in Saudi Arabia and southwest Iran (Abbasi et al., 2021b).
 224 Specifically, the fibres shown in Figures 3a and 3b exhibit smooth surfaces with very little
 225 evidence of weathering but contamination by extraneous material apparent in the latter case, while
 226 the fibres shown in Figures 3c and 3d exhibit contamination and considerable but heterogeneous

227 weathering. In Figure 3c, indentations and pits are indicators of mechanical weathering while
228 flaking and granulation are more typical of photo-oxidation (Zbyszewski and Corcoran, 2011). In
229 Figure 3d, we suspect that the almost parallel but irregular, circular fractures normal to the length
230 of fibre result from shrinkage-expansion while exposed to extreme environmental temperatures.
231 The plastic films illustrated in Figures 3e and 3f contrast the effects of intense photo-oxidation
232 (granulation and flaking) and mechanical weathering (grooves and indentations) on the surface
233 morphologies of thin, angular plastic films.

234



235

236 **Figure 3:** SEM images of six MP retrieved from material deposited in Shiraz after the dust storm.
 237 (a) Green polypropylene fibre, (b) red polypropylene fibre, (c) white polyethylene terephthalate
 238 fibre, (d) green polypropylene fibre, (e) colourless polypropylene film, (f) purple nylon film.

239 *3.2. Origin of dust and microplastics*

240 The air mass trajectory frequencies for the period directly preceding the dust storm and calculated
241 using HYSPLIT are shown in Figure 4a. These frequencies indicate dominant westerly and
242 southwesterly components associated with the event, with satellite imagery (Figure 4b) and
243 geochemical signatures reported in Abbasi et al. (2021b) confirming that the most important source
244 of dust is the Arabian Peninsula, and in particular the Saudi Arabian deserts. Here, resuspension
245 of material is favoured by extensive accumulations of fine sand and silt, scattered vegetation and
246 variable terrain (Engelbrecht et al., 2017).

247 The MPs deposited in Shiraz following the dust storm may, therefore, have both distant (or remote)
248 and more local origins. Distant MPs are carried by strong winds with geogenic material (e.g.,
249 silicates, aluminosilicates, carbonates) from the Arabian Peninsula, and may be augmented by
250 entrainment of additional plastics in southwest Iran and, potentially, through breaking waves at
251 sea (Allen et al., 2020) as air moves across the Persian Gulf. Local MPs are resuspended with
252 natural soils (mainly silt and clay) and anthropogenic particulates within the urbanized region of
253 Shiraz as the dust storm passes through the metropolis. Nematollahi et al. (2021) found a clear
254 linear correlation between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ isotopes measured in deposited dust particles in Shiraz
255 arising from the dust storm reported here that was attributed to the mixing of two particle end-
256 members: namely, an “anthropogenic” population and a less contaminated but more “geogenic”
257 population. Likewise, it is proposed that MPs in deposited dust particles in Shiraz following the
258 dust storm are derived from and can be modelled by two end-member mixing.

259

260

261 3.3. *End-member microplastic mixing model*

262 In the present context, the end-members of MPs observed at a location impacted by a dust storm
263 can be defined as those associated with geogenic material that are imported by the atmosphere
264 with strong winds, and those already resident at the location but suspended by the event itself (and
265 including any material sampled from car windows that was present before the dust storm). The
266 two populations of MP may be different because of distinctly different sources, histories and ages,
267 but are more likely to exhibit some similarities because of the global reach of plastic products and
268 common means of generating MP, coupled with the mixing effects of previous dust events at the
269 location of interest. Without characterizing the end-members themselves, it is not possible to
270 establish any clear differences in these populations. However, SEM observations suggest that MPs
271 imported from the Arabian deserts could exhibit distinctive weathering patterns (such as the
272 shrinkage observed in Figure 3d), while a greater proportion of smaller, fibrous MPs observed in
273 the present study compared with MPs in settled **dust particles** of Shiraz suggests that imported
274 particles are relatively fine. Conversely, more general aerodynamic considerations and
275 observations in the literature suggest that more rapidly settling, larger fibres and non-fibrous
276 particles are likely to have a local origin (Brahney et al., 2020; Loppi et al., 2021). Nevertheless,
277 and regardless of these characteristics, binary mixing can be considered numerically from MP
278 concentrations representative of the end-member populations.

279 Thus, typical concentrations of MPs on a number basis in background settled urban **dust particles**
280 from Shiraz are about 25 MP g⁻¹ (Abbasi and Turner, 2021), which is similar to the median
281 concentration of MP measured in street dusts from the industrialized city of Asaluyeh, western
282 Iran (about 15 MP g⁻¹; Abbasi et al., 2019), while concentrations in desert soils remote from any
283 urbanization and derived from the dispersion of distal sources average about 0.02 MP g⁻¹ (Abbasi

284 et al., 2021a). Assuming that dust and MPs exhibit similar entrainments into the atmosphere, the
285 fractional contribution, f , of each end-member to the net concentration of MP observed in the dust
286 storm, $[MP]_{dust}$, can be modelled as follows:

$$287 \quad [MP]_{dust} = f_{rem}[MP]_{rem} + f_{loc}[MP]_{loc} \quad (2)$$

288 where subscripts rem and loc refer to remote and local sources, respectively. Substituting $1-f_{loc}$
289 for f_{rem} :

$$290 \quad [MP]_{dust} = [MP]_{rem} - f_{loc}[MP]_{rem} + f_{loc}[MP]_{loc} \quad (3)$$

291 and rearranging yields:

$$292 \quad f_{loc} = ([MP]_{dust} - [MP]_{rem}) / ([MP]_{loc} - [MP]_{rem}) \quad (4)$$

293 Using the typical or average end-member MP concentrations above for $[MP]_{loc}$ and $[MP]_{rem}$ of 20
294 and 0.02 MP g⁻¹, respectively, and the median MP concentration in Table 1 as $[MP]_{dust}$ (0.31 MP
295 g⁻¹) results in a value of f_{loc} of 0.015; using the lowest and highest MP concentrations in Table 1
296 for $[MP]_{dust}$ (0.04 and 1.06 MP g⁻¹, respectively) results in values of about 0.001 and 0.05,
297 respectively. Thus, the estimated range in contributions of MP that are local to Shiraz to the
298 sampled **dust particles** is about 0.1 to 5%, with variations amongst the locations presumably
299 reflecting differences in the proximity to or mobility of urban sources but displaying no clear
300 relationship with particle characteristics (e.g., size, colour or shape). The majority of MP are,
301 however, clearly imported from outside the region (and via Saudi Arabia and southwest Iran), with
302 geochemical analyses of dust samples suggesting that the Arabian Peninsula provides the more
303 significant, **transboundary** contribution (Abbasi et al., 2021b).

304

305

306 *3.4. Wider implications*

307 The numerical estimates of MP origin are subject to various assumptions, including processes
308 involved in the suspension-transport-deposition that are similar for both geogenic material and
309 MPs. Nevertheless, they highlight the importance of dust events to the redistribution of MP in arid
310 and semi-arid regions and add to the growing body of evidence in the literature supporting the
311 more general long-range and transboundary atmospheric transport of fibrous MP (Allen et al.,
312 2019; Brahney et al., 2020; Evangeliou et al., 2020).

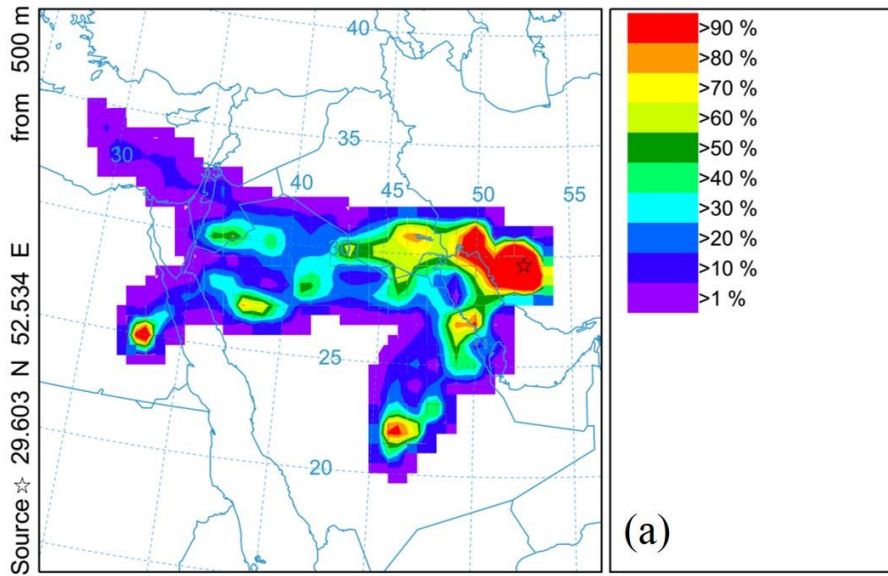
313 Although the mass of mobile dust involved in the storm under study does not appear to have been
314 estimated, an earlier event occurring in the Arabian Peninsula and simulated by Jish Prakash et al.
315 (2015) suggested that nearly 100 Mt of dust was emitted, with 73 Mt deposited over the broader
316 region of study and including about 7 Mt deposited in the ocean. Assuming that the concentration
317 of MP in the soils acting as a source of dust is about 0.02 MP g⁻¹ (Abbasi et al., 2021b), we estimate
318 that such a storm could suspend about 2 x 10¹² MP and deposit 1.5 x 10¹² MP regionally, including
319 1.5 x 10¹¹ MP in the ocean. Globally, it is estimated that about 2 billion tonnes of loose and poorly
320 vegetated arid soil are transported in the atmosphere each year (Perkins, 2001; Tanaka and Chiba,
321 2006), with the main source regions associated with the Sahara desert and the deserts of Asia, the
322 Middle East, North and South America and Australia (Wang, 2015). Assuming that the soil
323 concentration of MPs employed in the present study is more generally applicable, dust storms
324 could be responsible for the annual, atmospheric mobilization and transportation of about 4 x 10¹³
325 MP. For representative fibrous MPs of unit density and 250 µm in length and 10 µm in diameter,
326 this is equivalent to about a tonne of MPs. Dust storms, therefore, represents a significant means

327 by which MPs are redistributed in the environment and, given the proximity of many dust sources
328 to the coastal zone, a potentially important, indirect source of MPs to the ocean. Moreover, with
329 the intensity and frequency of droughts predicted to increase (Srivasta et al., 2018), along with
330 increasing demands for water (Hoff, 2009) and plastic (Geyer et al., 2017), dust storms are likely
331 to be of increasing importance to the global flux and cycling of environmental MPs.

332 The current study is also significant in highlighting the presence of a type of contaminant
333 suspended in dust storms that has thus far been overlooked. The precise health impacts of airborne
334 MPs, and in particular those that are inhalable, are unclear (Wright et al., 2019; Rahman et al.,
335 2021), but any effects associated with **dust storms** should be considered along with those arising
336 from the presence of other materials and chemicals, **including dust itself, allergenic particles, like**
337 **pollen and fungi, microbiological organisms, and heavy metals (Kellogg and Griffin, 2006).**

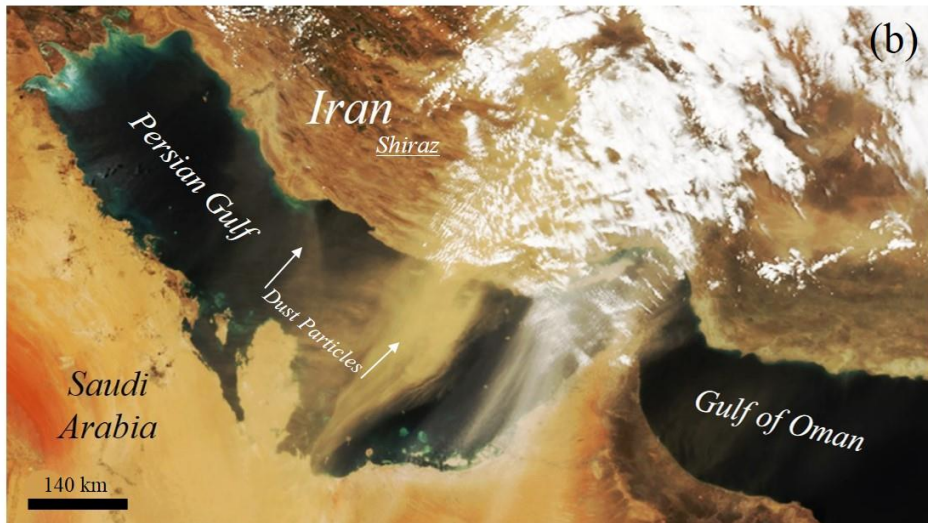
338

NOAA HYSPLIT MODEL - TRAJECTORY FREQUENCIES
 # endpts per grid sq./# trajectories (%) 0 m and 99999 m
 Integrated from 1400 12 May to 2000 08 May 18 (UTC) [backward]
 Freq Calculation started at 0000 00 00 (UTC)



METEOROLOGICAL DATA

Job ID: 196611 Job Start: Mon Jun 14 14:16:38 UTC 2021
 Source 1 lat.: 29.602715 lon.: 52.534218 height: 500 m AGL
 Initial trajectory started: 1400Z 12 May 18
 Direction of trajectories: Backward Trajectory Duration: 48 hrs
 Frequency grid resolution: 1.0 x 1.0 degrees
 Endpoint output frequency: 60 per hour
 Number of trajectories used for this calculation: 8
 Meteorology: 0000Z 12 May 2018 - GDAS0p5



339

340 **Figure 4:** (a) Frequencies of air trajectories crossing a given area and arriving at Shiraz (starred)
 341 for 8th to 12th May 2018 calculated at 500 m and from 48 h air mass back-trajectories using
 342 HYSPLIT, and (b) NOAA satellite image of the region during the **dust storm**.

343

344

345 **4. Conclusions**

346 This study is the first to document MPs associated with and transported by a dust storm. With
347 respect to an intense event in the metropolis of Shiraz in May 2018, the majority of plastics isolated
348 from deposited **dust particles** were fibrous, with concentrations on a number basis ranging from <
349 0.05 to about 1.1 MP g⁻¹. MPs exhibited varying degrees of mechanical weathering, photo-
350 oxidation and contamination by geogenic particulates, and the provenance of the latter, coupled
351 with satellite imagery and HYSPLIT modelling, suggests that the majority of material brought into
352 Shiraz originates from the Saudi Arabian Peninsula. Within the uncertainties and assumption of a
353 two end-member MP mixing model, we estimate that > 90% of plastics **in deposited dusts** are
354 derived from outside the city. Globally, dust storms could represent a significant means of MP
355 transportation in the atmosphere and an important source of MPs to the ocean.

356

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360

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