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Microplastics in the Lut and Kavir Deserts, Iran

Sajjad Abbasi ^{a, *}, Andrew Turner ^b, Mohammad Hoseini ^c, Hoda Amiri ^{d, e, *}

^a Department of Earth Sciences, College of Science, Shiraz University, Shiraz 71454, Iran

^b School of Geography, Earth and Environmental Sciences, University of Plymouth, PL4 8AA, UK

^c Department of Environmental Health, Research Center for Health Sciences, Institute of Health, School of Health, Shiraz University of Medical Sciences, Shiraz, Iran

^d Environmental Health Engineering Research Center, Kerman University of Medical Sciences, Kerman, Iran

^e Department of Environmental Health, School of Public Health, Kerman University of Medical Sciences, Kerman, Iran

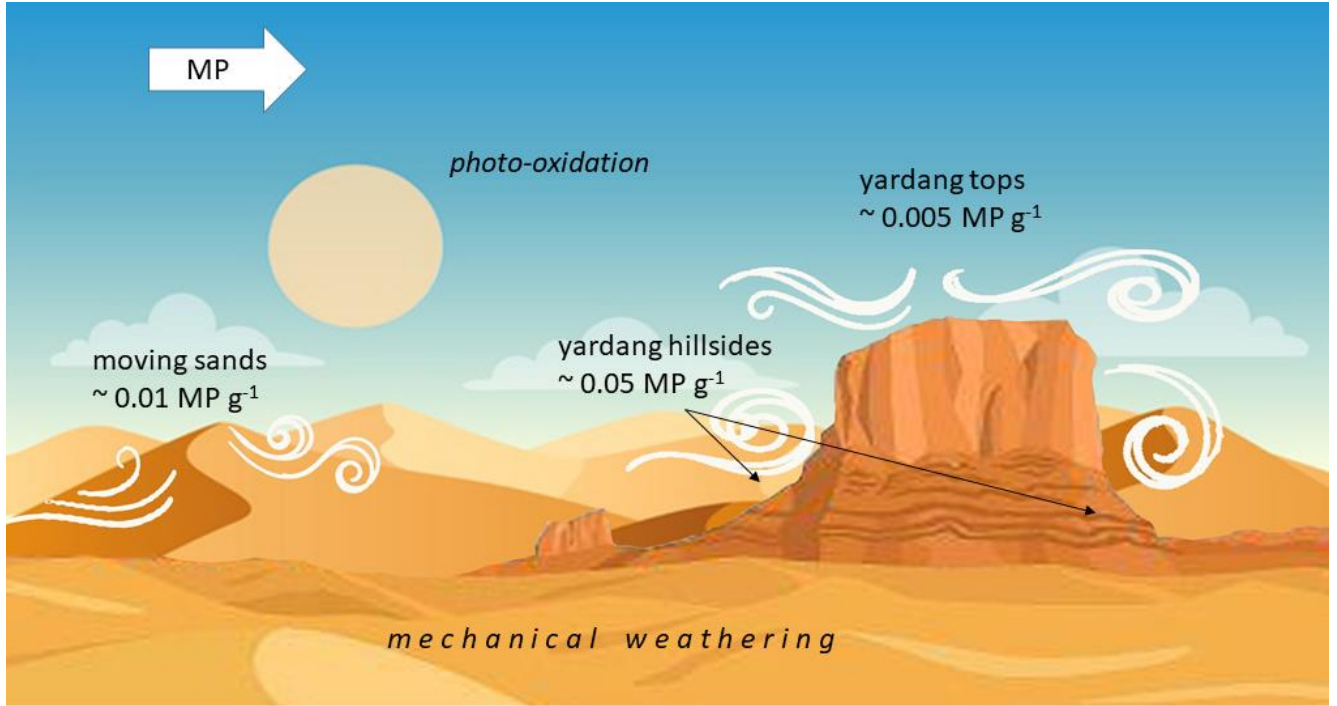
* Corresponding authors: sajjad.abbasi@shirazu.ac.ir;

hoda.amiri@gmail.com

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22 **Graphical Abstract**



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37 **Abstract**

38 Although microplastics (MP) are ubiquitous environmental contaminants, little is known about
39 their occurrence and behaviour in remote, terrestrial environments. In this study, MP have been
40 isolated from soils collected from various geomorphological features (yardangs, sand dunes,
41 moving sands, seasonal lakes) of the Kavir and Lut Deserts on the Iranian plateau. The number of
42 MP identified in 300 g samples ranged from zero (not detected) in several yardang tops to 25 on
43 some yardang hillsides, with an overall average abundance of about 0.02 MP g⁻¹. The majority of
44 MP were of a fibrous nature with a size distribution ($\leq 100 \mu\text{m}$ to $\geq 1000 \mu\text{m}$) skewed towards the
45 lower end, and analysis of a selection of particles by μ -Raman spectroscopy showed that
46 polyethylene terephthalate and Nylon (polyamide) were the principal polymers. Scanning electron
47 microscopy revealed intense degradation of some particles but limited weathering of others. With
48 little evidence of meso- and macroplastics in the deserts, it appears that the majority of MP are
49 brought into these environments from distant sources via the wind, with smaller, seasonal
50 contributions from runoff associated with the adjacent mountains. It is proposed that some
51 windborne MP are transported through the deserts relatively rapidly while others are subject to
52 internal recycling and significant photo-oxidation and mechanical weathering.

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61 **Introduction**

62 **Microplastics (MP) have become increasingly studied in soils over the past few years because of**
63 **their threats to terrestrial ecosystems**^{1,2,3}. Sources of MP in soils include littering and tipping, use
64 of plastic-based mulches, application of sewage sludge, inundation by floodwater, road runoff and
65 irrigation water, and atmospheric deposition^{4,5}. Soils are most contaminated by MP in the vicinity
66 of population centers and certain industries **or where intensive farming takes place**^{6,7}. However,
67 MP have also been detected in soils from regions remote from development, including Chilean
68 rangelands and grasslands⁸ and the Tibetan plateau⁹. Here, the principal means of contamination
69 is believed to be the long-range aeolian transport of particles with air masses having origins in or
70 passing through more developed regions¹⁰. Deposition may occur with dusts under dry conditions
71 or with precipitation, with the relative significance of each pathways dependent on climate^{11,12}.
72 Regardless of the mode of deposition, the capture and subsequent fate of MP are likely to be
73 affected by the moisture content of the soil, either directly as a porous solid or indirectly by the
74 nature and extent of vegetative cover¹³.

75 One remote type of environment that has received very little systematic study in respect of MP is
76 the desert, and in particular the subtropical desert. In the latter, conditions are likely to be amongst
77 the most favorable for plastic degradation on the planet, with high (but variable) temperatures,
78 high levels of insolation, and intense frictional forces and abrasion engendered by interactions
79 between wind and sand. Zylstra¹⁴ reported on the distributions of plastic bags and balloons in the
80 Sonoran Desert, Arizona, and proposed that such items might be a source of MP through
81 photodegradation. However, and more generally, external, airborne sources of MP in deserts have
82 thus far not been considered.

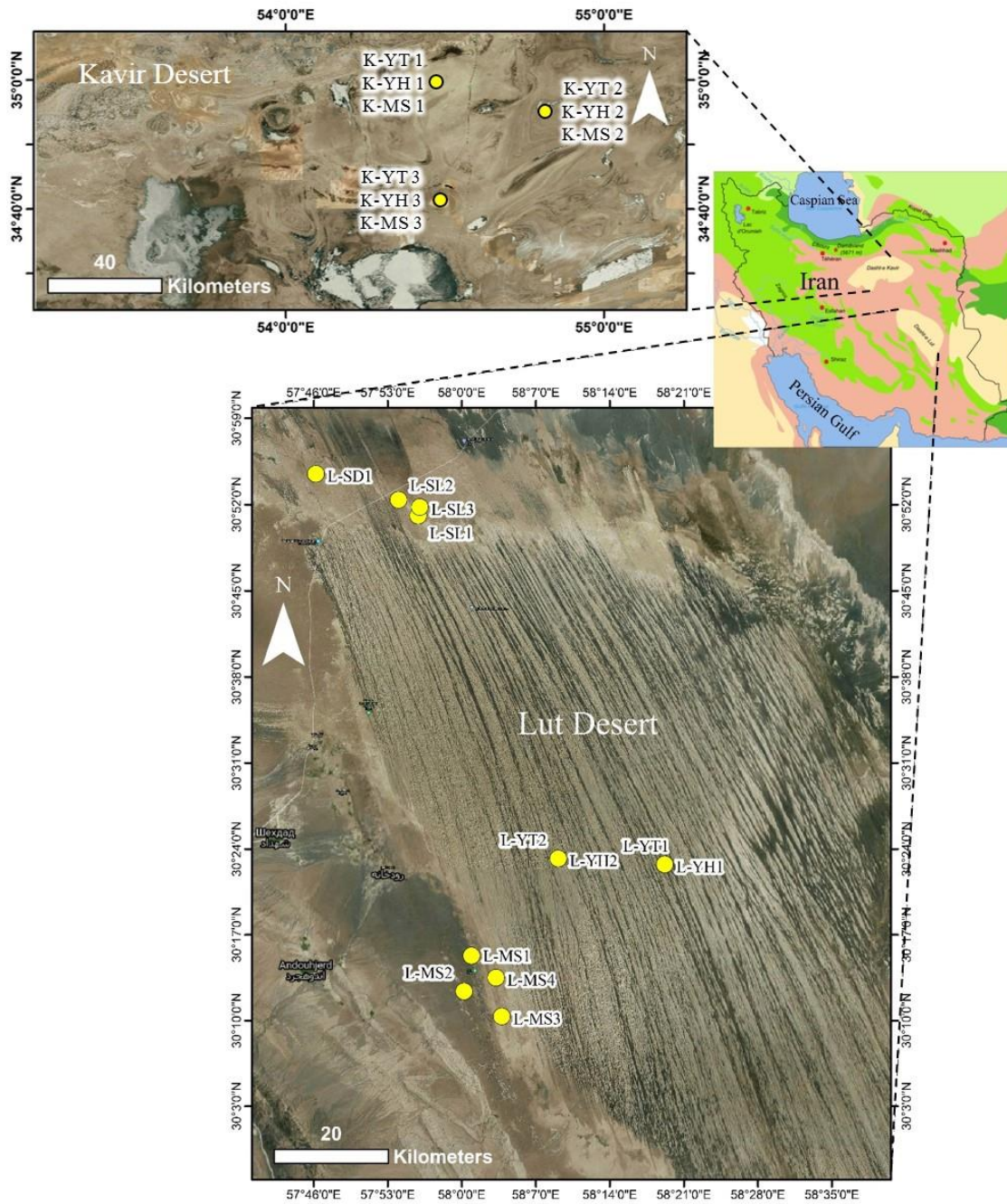
83 In the present study, **soils were collected** from two remote, subtropical deserts in Iran in order to
84 determine the presence, quantities and characteristics MP in this type of environment. Specifically,
85 samples **were collected** from different geomorphological features and on a monthly basis
86 throughout the year and MP isolated, categorized and analysed using established techniques. The
87 broad origins of the MP **were also investigated** by computing back trajectories from the study
88 regions.

89

90 **Experimental section**

91 *Sampling sites*

92 Two deserts on the Iranian plateau (Figure 1) were considered in the present study whose climates
93 and geomorphologies are described in detail elsewhere^{15, 16, 17} and are summarized as follows. The
94 **Dasht-e-Kavir** (Kavir) occupies about 80,000 km² and has a minimum elevation of 800 m. It is
95 characterized by pebbly steppes and salt deserts and, in the northern reaches, sand dunes and
96 shifting sands. Northerly winds transport sand to the southwest of the region, but much of the
97 desert is covered with grey-colored calcareous soils. The **Dasht-e-Lut** (Lut) occupies about 50,000
98 km² and lies between about 100 m and 500 m in elevation. It is hyperarid and is largely made up
99 of gravel and sandy desert. Strong northerly and northwesterly winds blow sand southwards, and
100 in particular between June and October, forming dunes and shifting sands. Both deserts are
101 characterized by long and hot summers (with temperatures often exceeding **50°C**), but winter
102 runoff from surrounding mountains can create seasonal lakes or marshes. Because of the harsh
103 conditions, communities are generally limited to the peripheries of the deserts.



104

105 Figure 1: Locations of the soil samples taken in the Kavir (K-) and Lut (L-) deserts. YT = yardang
 106 top; YH = yardang hillside; MS = moving sand; SD = sand dune; SL = seasonal lake. **UTM**
 107 **coordinates of the sampling locations are shown in Table S2.**

108

109

110 *Sampling*

111 With the assistance of the Kerman Tourist Guides Association, deserts were accessed in an off-
112 road vehicle through the main and subsidiary road network, with sampling locations usually 300-
113 500 m away from the access road. Samples were taken from the locations shown in Figure 1 by an
114 operator wearing cotton clothing and at a suitable distance (> 50 m) from and upwind of the off-
115 road vehicle.

116 An initial sampling campaign consisted of the collection of 21 sandy to clayey soils from the Kavir
117 and Lut deserts during the dry season (September 2019). Geomorphological features considered
118 were moving sands, yardang tops (up to 50 m in elevation) and **yardang hillsides** (Kavir and Lut),
119 and sand dunes and seasonal lakes (Lut only). About 300 mL of topsoil (**depth** < 5 cm) was
120 collected with a metallic trowel and transferred into a pre-cleaned glass jar, with the trowel cleaned
121 with filtered water between samples. Sample jars were covered with Al foil and transported to the
122 laboratory where microplastic extraction and identification was undertaken according to protocols
123 described below. **Additionally, and between October 2019 and August 2020 in the Kavir desert,**
124 **sampling continued** towards the end of each month at the locations and geomorphological features
125 shown in Figure 1.

126

127 *Sample treatment and microplastic extraction*

128 In a clean laboratory, soil samples were transferred to individual, 600-mL glass beakers using a
129 stainless steel spoon and dried for 24 h at **25°C**. Dried samples were sieved through a 5-mm
130 stainless steel mesh to remove coarse material like stones and plant debris (**and identify any meso-**

131 plastics) before being stored in clean 600-mL glass beakers that were covered with Al foil. Organic
132 matter was destroyed by oxidation of 300 g of each sample with 200-300 mL of 30 % H₂O₂ (Arman
133 Sina, Tehran) at room temperature until bubble formation ceased. Residual material was washed
134 through a 150 mm diameter S&S filter paper (blue band, grade 589/3, 2 μm pore size) using
135 filtered, deionized water before being dried in a sand bath at 60°C for 2 h. MPs were subsequently
136 separated by flotation for 24 h in a saturated 300 mL solution of ZnCl₂ (Arman Sina, Tehran;
137 density 1.6 – 1.8 g cm⁻³) in clean glass beakers after an initial 5-min period of agitation at 350 rpm.
138 Decanted contents were subsequently centrifuged for 5 min at 4000 rpm and supernatants vacuum-
139 filtered through S&S filter papers. To ensure maximum recovery of MP, this process was repeated
140 twice, with resulting filters air-dried for 48 h at 25°C in a clean room under laminar flow and
141 transferred to glass Petri dishes for physical and chemical characterisation.

142

143 *Microplastic identification*

144 MP on filters were visually identified and counted under a binocular microscope (Carl-Zeiss) at
145 up to 200 x magnification using a 250 μm stainless steel probe and ImageJ software, with
146 identification criteria based on thickness and cross sectional properties, shininess, hardness,
147 reaction to a hot needle, and surface structure¹⁸. Size was recorded according to length along the
148 longest axis, L (L ≤ 100 μm, 100 < L ≤ 250 μm, 250 ≤ L < 500 μm, 500 ≤ L < 1000 μm, L ≥ 1000 μm),
149 color was categorized as black-grey, yellow-orange, white-transparent, red-pink or blue-green, and
150 shape or type was classified as fibre, primary (pellet, granule) or secondary (fragment, film).

151 Surface and morphological characteristics, chemical composition and polymeric construction were
152 determined on a range of randomly selected MP from different locations and of different color,

153 size and form ($n = 21$) using a μ -Raman spectrometer and scanning electron microscope (SEM).
154 The μ -Raman spectrometer (LabRAM HR, Horiba, Japan) employed a laser of 785 nm and Raman
155 shift of 400-1800 cm^{-1} with acquisition times between 20 and 30 s. The polymeric composition of
156 the sample was determined by comparing the vibrational spectrum with reference spectra in the
157 instrument library and using a threshold match criterion of 0.80. The high vacuum SEM (TESCAN
158 Vega 3, Czech Republic) was operated with a resolution of 2 nm at 20 kV and equipped with an
159 energy-dispersive X-ray microanalyser (EDX). Here, MP were mounted on double-sided copper
160 adhesive tape on microscope slides and gold-coated.

161

162 *Quality control*

163 Laboratory equipment and containers were washed with phosphate-free soap, double rinsed with
164 filtered water and soaked in 10% Merck Suprapur HNO_3 for 24 h before being rinsed twice with
165 double-distilled water, dried at room temperature in a clean room and, where appropriate, protected
166 by Al foil. Laboratory benches were cleaned thoroughly with ethanol, laboratory clothing was
167 cotton-based and all reagents and solutions were filtered through S&S blue band filters before
168 being used. Controls, consisting of *open-air blanks* processed as above, revealed no airborne MP
169 contamination.

170 MP recovery was also checked by adding ten MP of distinctive color, size and shape, and prepared
171 by milling of polyethylene terephthalate (PET), polyethylene, polypropylene and polyvinyl
172 chloride, to a 300 g sample of desert soil. The amended sample was processed as above and the
173 ten customized MP were successfully isolated and identified under the microscope.

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175 *Trajectory calculations*

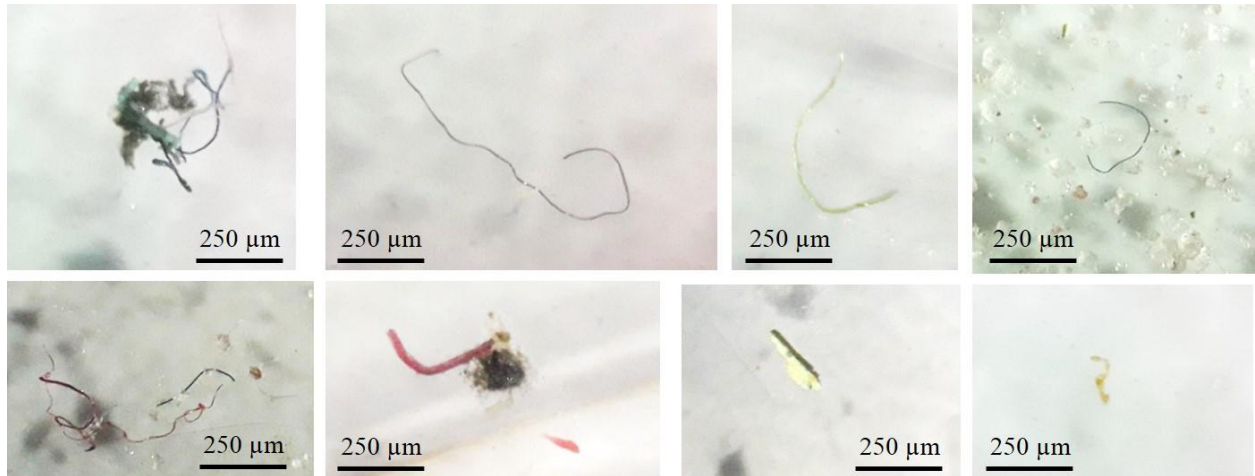
176 In order to assess the potential source range of MP to the study locations **in the Kavir and Lut**
177 **deserts**, 48-h back trajectories were calculated using the National Oceanic and Atmospheric
178 Administration online software, Hybrid Single Particle Lagrangian Integrated Trajectory
179 (HYSPLIT) and Global Forecast System (0.25 degree global) meteorological data. Trajectories
180 were calculated at six-hour intervals at a height of 500 m above ground level and a resolution of 1
181 degree and were integrated as frequency distributions for each month preceding the sampling date.

182

183 **Results**

184 Examples of MP retrieved from the desert soils and as viewed under the binocular microscope are
185 shown in Figure 2. The majority of particles were fibres of varying length, thickness and color that
186 were often coiled or twisted. Of the 21 MP retrieved from **Kavir and Lut soils** and analysed for
187 polymeric makeup **by μ -Raman spectroscopy** (and comprising 18 fibres and three fragments),
188 eleven were identified as PET, **seven were Nylon**, two were polystyrene and one was
189 polypropylene.

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192 Figure 2: Microscopic images of selected fibrous and fragmented MP sampled from the **Kavir and**
 193 **Lut deserts.**

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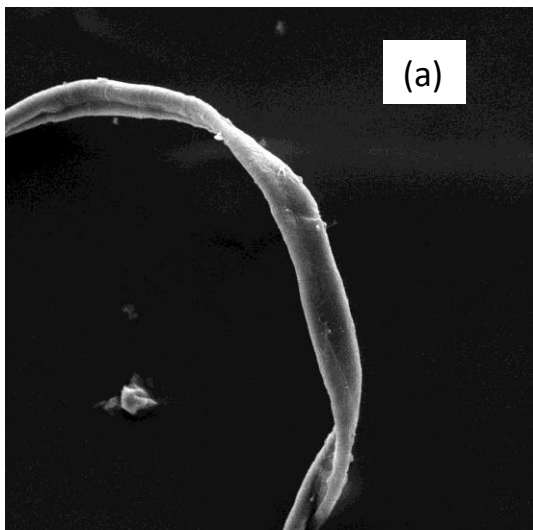
195 Under the SEM, and as exemplified in Figure 3, the surfaces of some of the fibres examined
 196 appeared smooth but with adhered particulates returning EDX peaks (e.g., Al, Ca, Cl, Fe, Mg, Ti,
 197 Zn) characteristic of soil and, possibly, residual salts (including $ZnCl_2$) that formed during sample
 198 processing. Other fibres, however, along with fragmented MP, appeared to have undergone
 199 significant and heterogeneous weathering and fragmentation, resulting in surfaces that were rough
 200 and irregular and, in some cases, pitted and notched, but that still contained evidence of adherent
 201 or trapped soil particulates.

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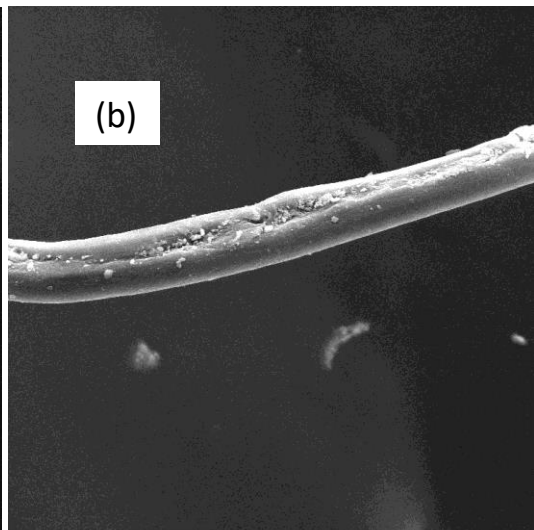
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(a)

SEM HV: 20.0 kV WD: 15.33 mm VEGA3 TESCAN
 View field: 189 μm Det: SE 50 μm
 SEM MAG: 1.00 kx Date(m/d/y): 10/20/20

206



(b)

SEM HV: 20.0 kV WD: 15.14 mm VEGA3 TESCAN
 View field: 190 μm Det: SE 50 μm
 SEM MAG: 1.00 kx Date(m/d/y): 10/20/20

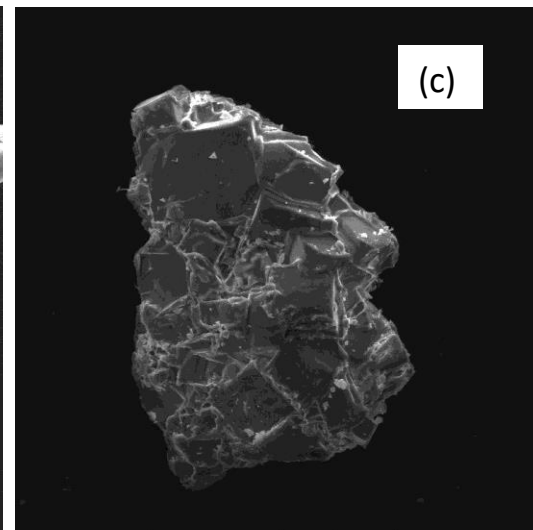
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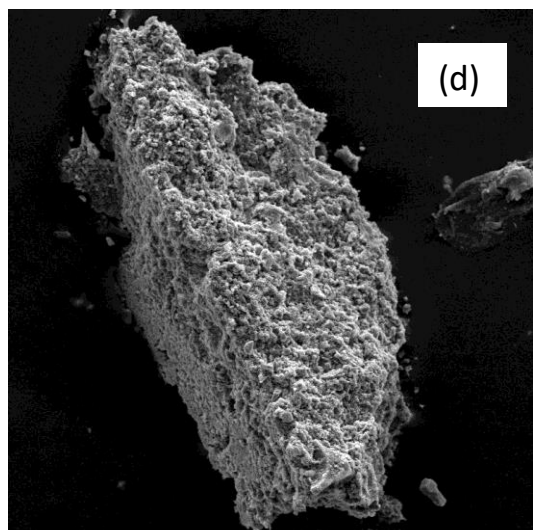
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(c)

SEM HV: 20.0 kV WD: 15.20 mm VEGA3 TESCAN
 View field: 452 μm Det: SE 100 μm
 SEM MAG: 420 x Date(m/d/y): 10/20/20

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(d)

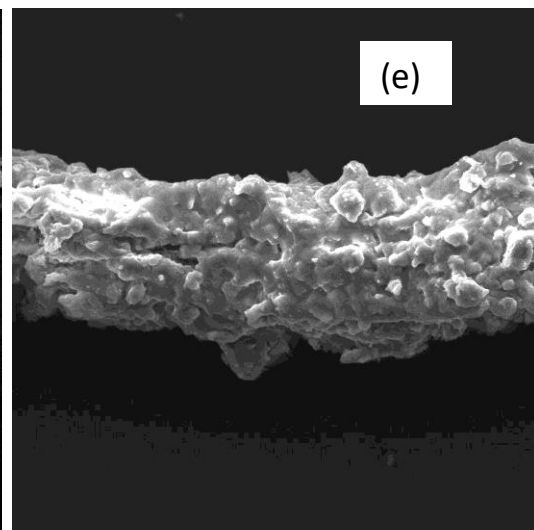
SEM HV: 20.0 kV WD: 15.14 mm VEGA3 TESCAN
 View field: 486 μm Det: SE 100 μm
 SEM MAG: 390 x Date(m/d/y): 10/20/20

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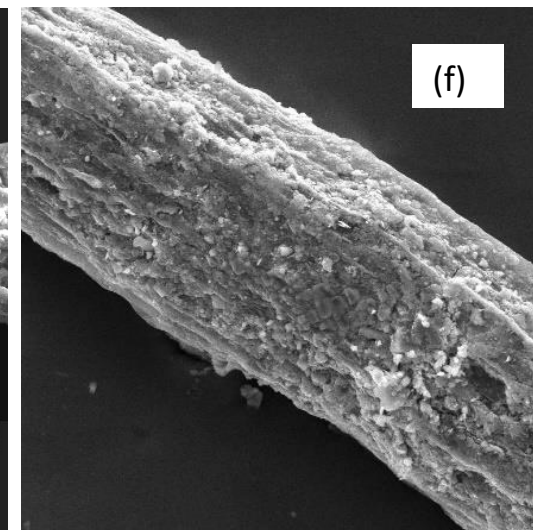
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(e)

SEM HV: 20.0 kV WD: 15.30 mm VEGA3 TESCAN
 View field: 189 μm Det: SE 50 μm
 SEM MAG: 1.00 kx Date(m/d/y): 10/20/20



(f)

SEM HV: 20.0 kV WD: 15.23 mm VEGA3 TESCAN
 View field: 190 μm Det: SE 50 μm
 SEM MAG: 1.00 kx Date(m/d/y): 10/20/20

217 Figure 3: SEM images of six MP retrieved from the Kavir and Lut deserts. (a) A smooth, yellow
218 Nylon fibre from a yardang top contaminated with soil particulates; (b) a smooth, white
219 polyethylene terephthalate fibre from a yardang top contaminated with soil particulates; (c) an
220 abraded, pink fragment of unknown polymeric composition from a yardang hillside and
221 contaminated by soil particulates; (d) a weathered, white polypropylene fragment from a yardang
222 hillside; (e) a weathered, green polystyrene fibre from a yardang hillside; and (f) a weathered,
223 yellow polyethylene terephthalate fibre from a yardang hillside.

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225 A summary of the numbers and types of MP identified in the 300-g soil samples collected from
226 the different locations and geomorphological features in the Lut Desert in September 2019 is given
227 in Table 1. There were 67 MP in total, with fibres dominating shape or form (96%) and the three
228 non-fibrous MP classified as fragments. Features with the greatest number of MP were the
229 hillsides of the yardangs and two out of the four moving sands. Moreover, yardang hillsides and
230 moving sands were the only features where MP fragments were observed. Nineteen MP, that
231 included two fragments, were in the smallest size category ($L \leq 100 \mu\text{m}$) and four MP were in the
232 largest category ($L \geq 1000 \mu\text{m}$); six samples were white or transparent, 27 were black or grey and
233 the remainder consisted of a variety of colors (but mainly red/pink and blue/green and that included
234 all fragmented MP).

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244 Table 1: Number of MP and their type, size and color distribution in 300-g soil samples from each
 245 site in the Lut desert, sampled in September 2019. YT = yardang top; YH = yardang hillside; MS
 246 = moving sand; SD = sand dune; SL = seasonal lake.

sample	MP	fibres	$L \leq 100 \mu\text{m}$	$L \geq 1000 \mu\text{m}$	white-transp	black-grey
L-YT1	4	4	2	1	1	2
L-YT2	2	2	1	0	0	2
L-YH1	9	8	3	0	0	4
L-YH2	13	12	1	0	3	3
L-SD1	3	3	2	0	1	0
L-MS1	16	16	3	1	0	9
L-MS2	3	2	1	0	0	1
L-MS3	1	1	1	0	0	1
L-MS4	6	6	3	1	0	4
L-SL1	3	3	2	0	0	1
L-SL2	4	4	0	0	0	0
L-SL3	3	3	0	1	1	0
total	67	64	19	4	6	27

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 248
 249 Figure 4 shows the average number of MP identified in the soils from the three yardang tops,
 250 yarding hillsides and moving sands in the Kavir desert that were sampled monthly over a year-
 251 long period. MP were most abundant in hillside soils throughout, with a distinct maximum
 252 occurring in February-March. Table 2 presents the total number of MP identified in the Kavir
 253 desert each month, along with abundance according to type, color and size. There were no clear
 254 temporal trends in these data and, overall, 617 MP were detected with an average abundance on a
 255 number basis of 0.02 g^{-1} . Over 93% of MP were of a fibrous nature (with the remainder fragments
 256 or films), white-transparent was the most common color, and twice as many particles were present
 257 in the finest size fraction ($L \leq 100 \mu\text{m}$) than in the coarsest fraction ($L \geq 1000 \mu\text{m}$).

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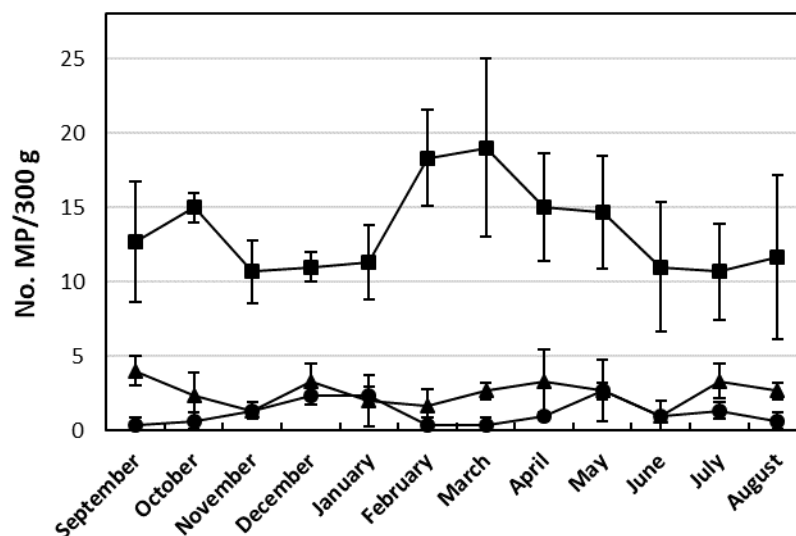


Figure 4: Average number of MP in 300-g soils sampled from yardang tops (●), yardang hillsides (■) and moving sands (▲) each month over a twelve-month period in the Kavir desert. Errors represent one standard deviation ($n = 3$).

Table 2: Total number of MP and their type, color and size distributions in the nine, 300-g Kavir desert soils (three each from yardang tops, yardang hillsides and moving sands) sampled over twelve months.

MP	September	October	November	December	January	February	March	April	May	June	July	August	total	%
total	51	54	40	50	47	61	66	58	60	39	46	45	617	100
fibres	45	48	37	49	45	57	62	53	59	39	40	42	576	93.4
fragments	6	3	2	1	2	3	3	3	1	0	3	2	29	4.7
films	0	3	1	0	0	1	1	2	0	0	3	1	12	1.9
white-transp	18	17	16	24	17	27	28	23	25	17	16	23	251	40.7
black-grey	13	14	9	12	9	14	25	19	20	13	12	8	168	27.2
other colours	20	23	15	14	21	20	13	16	15	9	18	14	198	32.1
$L \leq 100 \mu\text{m}$	11	14	20	17	11	20	22	16	19	12	12	11	185	30.0
$L \geq 1000 \mu\text{m}$	7	5	6	10	8	10	10	12	11	6	6	4	95	15.4
other sizes	33	35	14	23	28	31	34	30	30	21	28	30	337	54.6

Forty eight-hour back trajectory frequencies calculated using HYSPLIT for the Lut Desert in September 2019 are shown in Figure 5. Frequencies ($> 1\%$) extend in all directions with a range of about 1500 km to the west and northwest. However, the highest frequencies ($> 50\%$) are associated with air masses from the northwest to northeast and with a range of about 300 to 600 km. Monthly model frequency outputs for the Kavir Desert are shown in Figure S1 of the

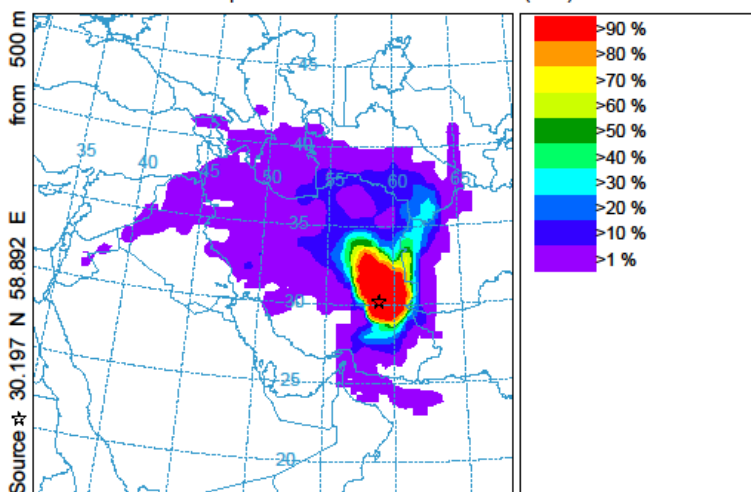
281 supporting information. The ranges of frequencies above 1% and above 50% are broadly similar
282 to those reported for the Lut Desert. However, there is a distinct seasonal pattern to trajectory
283 direction, with air from the north and northeast dominating from May to November and a notably
284 greater westerly component from December to April.

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NOAA HYSPLIT MODEL - TRAJECTORY FREQUENCIES
endpts per grid sq.# trajectories (%) 0 m and 99999 m
Integrated from 0500 30 Sep to 1100 01 Sep 19 (UTC) [backward]
Freq Calculation started at 0000 00 00 (UTC)

287



292

METEOROLOGICAL DATA

Job ID: 176201 Job Start: Thu Jan 21 06:24:59 UTC 2021
Source 1 lat.: 30.197366 lon.: 58.892212 height: 500 m AGL
Initial trajectory started: 0500Z 30 Sep 19
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: 108
Meteorology: 0000Z 30 Sep 2019 - GFS0p25

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294

295 **Figure 5: Frequencies of air trajectories crossing a given area and arriving at the sampling locations**
296 **in the Lut desert for September 2019, calculated from 48-hour air mass back-trajectories using**
297 **HYSPLIT.**

298

299 **Discussion**

300 MP have been detected in various remote environments, including the deep ocean ¹⁹, protected
301 wildernesses of the USA ¹⁰, mountain basins ²⁰ and the Arctic ²¹, but this paper is the first to report

302 their occurrence in the subtropical desert. Here, MP are dominated by fibres of various colors and
303 sizes (but skewed towards the lowest size fraction considered), with no granules, pellets or other
304 primary MP detected and no evidence of any larger (meso-) plastics amongst the samples. The
305 latter observation, and only occasional sightings of plastic litter (mainly bags) trapped behind
306 vegetation during the sampling campaigns, suggests that the majority of MPs are not formed in
307 situ through degradation and fragmentation but have been brought directly into the desert regions
308 from external sources. Moreover, the dominance of fibrous MP, whose relatively high surface area
309 to volume ratio increases drag forces and reduces settling velocity, suggests that wind is the
310 principal vector of transportation ^{21,22}. Aeolian transportation-deposition is consistent with the
311 greater occurrence of MP on the hillslopes of yardangs, where enhanced particle deposition takes
312 place ²³, and more generally, a size distribution that is skewed towards the fine end ^{20, 24, 25}. This is
313 in contrast to many other remote regions where water is a more important vector for transportation
314 and deposition and the stock of soil-borne MP is dominated by fragments and films ^{26, 9}.

315 Recent estimates suggest that airborne MP fibres are capable of being transported up to 1000 km
316 from their point of origin ¹⁰ and that tire-wear particles, albeit shorter than the MP fibres reported
317 herein but of greater density and lower drag, may have atmospheric residence times ranging from
318 5.5 to 11 days ²⁷. With MP subject to long-range transport and atmospheric residence times on the
319 order of days and with limited scope for washout with precipitation, 48-hour back trajectory
320 calculations would appear to provide a reasonable indicator of particle origin in the current study.
321 Trajectories for the Kavir desert (Figure S1) suggest that MP are largely transported from more
322 populated and developed (including agricultural) regions to the north and northeast from May to
323 November, with a greater contribution from regions to the west from December to May.

324 Although wind appears to be the principal mode of transportation of MP into and within the
325 deserts, an additional, seasonal source that is likely more locally significant is the surrounding
326 mountains. Here, MP that have been deposited in the catchment locally or from farther afield are
327 carried, via winter runoff, into the peripheral regions of the deserts and into the seasonal lakes and
328 marshes. The ten MP retrieved from the seasonal lakes of the Lut did not, however, exhibit any
329 clear differences to MP collected from other regions and geomorphological features of the desert.

330 The number of MP identified in 300 g of dry desert soil ranged from zero (not detected) in several
331 yardang tops to 25 on some yardang hillsides. The latter is equivalent to 0.083 MP g^{-1} , and on this
332 basis the overall average abundance of MP in soils from the Kavir and Lut deserts is about 0.02
333 MP g^{-1} . Comparing this value with literature concentrations reported for soils remote from
334 population centers or not contaminated by agricultural or industrial practices or by floodwater is
335 not straightforward. This is because discrepancies exist in sampling design (e.g. soil volume),
336 sample processing (e.g. sieve size and use or means of removal of organic matter and plastic
337 flotation), operational definitions of MP and methods of and criteria for MP identification, and the
338 nature and degree of data reporting. Nevertheless, the average value derived herein for desert soil
339 is at the low end of the range of MP concentrations reported for Tibetan plateau soils (0.02 to 0.11
340 MP g^{-1} ; ⁹) and soils from remote regions of the Fars province of southern Iran ($\sim 0.1 \text{ MP g}^{-1}$; ²⁸)
341 and is an order of magnitude below the maximum concentrations reported for Swiss floodplain
342 soils (0.59 MP g^{-1} ; ²⁶) and Chilean grassland and rangeland soils (0.2 MP g^{-1} ; ²⁹). Lower
343 concentrations of MP in desert soils may be attributed to relatively little input via rainfall washout
344 ¹¹, dilution by a large stock of unconsolidated and mobile soil and sand particles, and the harsh
345 environmental conditions that act to weather MP into sizes that evade deposition or detection by
346 conventional means.

347 **Specific conditions that particles, including MP**, are exposed to in the desert include high levels of
348 UV radiation, high temperatures (that can exceed 80 °C in sand) and intense, wind-assisted
349 mechanical abrasion and sandblasting ^{30,31,32,33}. **Song et al.** ³⁴ empirically demonstrated that
350 exposure of polyethylene and polypropylene pre-production pellets of mm dimensions to UV light
351 and abrasive forces typical of a sandy temperate beach produced MP whose abundance increased
352 with decreasing size. Given the dimensions of the majority of particles formed over an exposure
353 period equivalent to several years in the environment (< 300 µm) and the depths to which UV
354 oxidation can produce embrittlement of polymers (> 100 µm), significant weathering of fibrous
355 and film-like MP is anticipated for equivalent timescales under much harsher desert conditions.

356 The surfaces of some MP examined by SEM, **and in particular those from yardang hillsides**,
357 exhibited signs of intense photochemical and mechanical weathering, but surfaces of other MP
358 appeared to be largely intact (Figure 3). This may partly reflect differences in resistance to particle
359 abrasion among the different polymers, with polystyrene exhibiting a particularly low resistance
360 in dry-sand abrasion tests ³⁵ and revealing significant damage in desert soil (Figure 3d). More
361 generally, however, these observations suggest that there may be two groups of MP in the desert
362 environment. Firstly, MP that are subject to internal recycling (**entrapment and redistribution**) and
363 pervasive weathering from more aggressive processes like sandblasting, impaction and burial.
364 These MP **may be relatively “old” and** are likely to be associated with highly dynamic features
365 **and depositional zones such as** moving sands and yardang hillsides³³. Secondly, MP that are more
366 transient and whose origins are more directly represented by recent back-trajectories. **Here, more**
367 **“juvenile” particles** are carried through the desert relatively rapidly with the prevailing winds and
368 may be intermittently entrained by temporary events or subject to less aggressive weathering
369 processes like creep and saltation. Presumably, these different pathways and fates are determined

370 by the original properties of the plastics (e.g. size, shape, density) and regional variations in climate
371 and geomorphology. However, further, longer-term studies would be required to verify this
372 assertion and determine the precise drivers for differential particle behavior.

373 Photo-oxidation and mechanical weathering in the desert may also act to fractionate MP according
374 to polymer strength, with less strong materials more readily fragmented into smaller particles (that
375 are too small to be detected by our methodology). Thus, polymers having a relatively high tensile
376 strength (PET = 55 MPa and Nylon = 70 MPa) were dominant amongst the desert MP
377 characterized by μ -Raman spectroscopy while those of lower tensile strength (polypropylene and
378 polystyrene, both 40 MPa) were present in only three cases. Significantly, polyethylene, the most
379 widely produced thermoplastic but whose tensile strength is only 15 MPa, was entirely absent in
380 the present study. By contrast, in remote soils impacted more by humidity and precipitation,
381 polyethylene appears to make a much more important, and sometimes dominant contribution to
382 the stock of detectable MP ^{9,10}.

383 In summary, the present study is the first to demonstrate the presence of MP in the subtropical
384 desert environment. MP in soils from the Kavir and Lut deserts are dominated by fibres of various
385 polymeric construction and are more concentrated on certain geomorphological features like the
386 yardang hillsides. With little evidence of macro-plastics, it appears that MP are largely brought
387 into the deserts from regional and more distant sources with the wind. Because some MP exhibit
388 relatively little degradation yet others exhibit intense and heterogeneous weathering, it is proposed
389 that there are two types of particle based on retention and fate. Thus, some MP are rather transient
390 and are carried through the desert with relatively little interaction with surface features while others
391 are internally recycled and are subject to significant photo-oxidation and mechanical weathering.

392

393 **Supporting Information**

394 UTM coordinates of the sampling locations and HYSPLIT model outputs for each month sampled
395 in the Kavir desert are supplied as Supporting Information.

396

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401

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