2021-09-10

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Abbasi, S

10.1016/j.scitotenv.2021.147358
Science of The Total Environment
Elsevier BV

Dry and wet deposition of microplastics in a semi-arid region (Shiraz, Iran)

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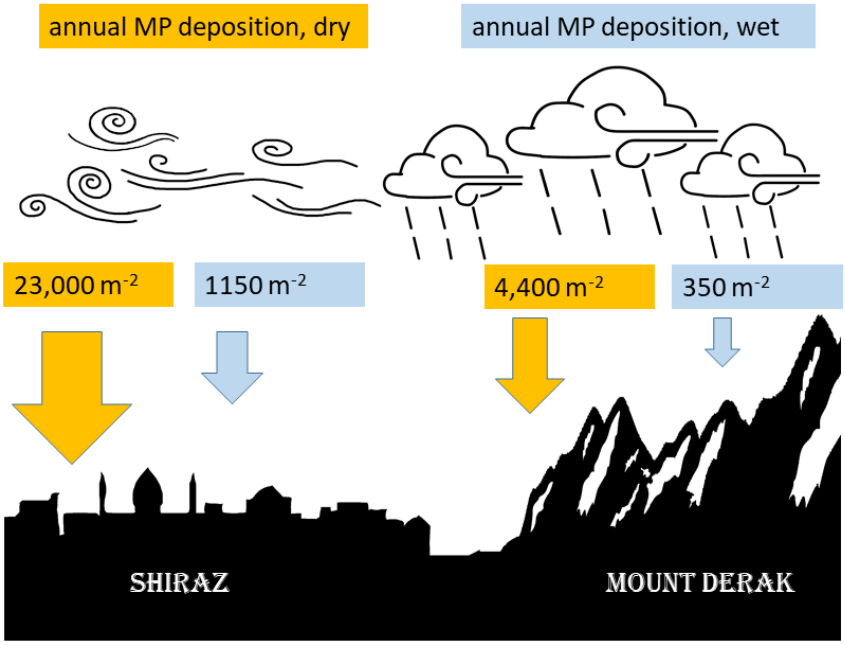
Accepted in STOTEN 30 April 2021

https://doi.org/10.1016/j.scitotenv.2021.147358

Graphical Abstract



Abstract

Microplastics (MP) have been retrieved from settled dusts and rainfall collected monthly over a period of a year and daily over an additional period of ten days in the city of Shiraz and at an elevated remote site (Mount Derak) in Iran. Total monthly deposition of ranged from about 1000 to 3500 MP m^{-2} at Shiraz and about 200 to 600 MP m^{-2} at Mount Derak, with greater deposition taking place during the dry months (June to November) than in months when precipitation events occurred. Overall, MP deposition was dominated by dry deposition, with precipitation appearing to washout MP and inhibit local resuspension of material by dampening the ground. The majority of MP in dust and precipitation (> 99%) were of a fibrous nature, with the finest particles measured (< 100 µm in length) comprising ~ 20-40% of MP at Shiraz and ~ 70-80% of MP at Mount Derak and analysis of selected samples (*n* = 34) revealing the most abundant polymers to be polypropylene, polyethylene, and polyethylene terephthalate. While in Shiraz, local sources of MP are likely significant, the occurrence of MP at Mount Derak and back trajectories computed with HYSPLIT suggest that distal sources, mainly carried by air masses from the north and west, are also important. The observations here add to the growing evidence of the global ubiquity and long-range transport of MP in the atmosphere and reinforce calls for more research into the potential impacts of MP in this environmental compartment.

Keywords: microplastics; fibres; dust; precipitation; deposition; atmosphere; Iran

1. Introduction

Microplastics (MP), ranging from 1 µm to 5 mm in size, are generated throughout the life cycle of plastic products, including production, usage, recycling and disposal. Consequently, they are pervasive and ubiquitous contaminants of the environment. The concentrations, distributions and impacts of MP have been well-documented in the marine environment and on marine biota over the past two decades (Fendall and Sewell, 2009; Cole et al., 2011; Cesa et al., 2017), with scientific attention subsequently

extending to freshwater systems (Li et al., 2018; Mendoza and Balcer, 2019) and the terrestrial environment (Hodson et al., 2017; Machado et al., 2018).

Because of their low density compared with soil and dust and, in particular for fibres, their high drag and low settling velocities, MP are readily emitted to, suspended in and transported by the atmosphere (Brahney et al., 2020). However, the presence, sources, modelling, impacts and fate of MP in this environmental compartment have received rather limited and only recent consideration in the literature (Zhang et al., 2020). Passive samplers have been employed to collect (through wet and dry deposition), quantify and characterise airborne MP in various urban areas (Dris et al., 2015; Klein and Fischer, 2019; Stanton et al., 2019; Wright et al., 2020) and at locations remote from any industrial activity or population centres (Klein and Fischer, 2019; Allen et al., 2020; Brahney et al., 2020) over periods of a few days to a few months. Detectable MP appear to be dominated by small (sub-mm) fibrous particles of varying polymeric makeup, with trajectory calculations suggesting both local and distal sources and the potential for long-range (> 1000 km) transport. A recent study also suggests that MP could be entering the atmosphere from the ocean (as a secondary source), along with salt and bacteria, through bubble burst ejection and wave action (Allen et al., 2020).

In order to improve our understanding of the transport, deposition and nature of atmospheric MP, we report on their occurrence in both dry deposition (through gravitational settling) and wet deposition (with precipitation) from a semi-arid region that experiences distinct climatic seasons. MP are monitored on a monthly basis over a year and on a daily basis over an additional ten-day period in an urban location and at an elevated, remote site. MP are classified by size and shape, with a selection subject to polymeric characterisation, and sources are investigated by computing back trajectories.

2. Methods

2.1. Sample locations

Samples were collected from the urban metropolis of Shiraz, southwest Iran, and a remote but relatively accessible station on Mount Derak, 20 km to the northwest of the city (Figure 1). Shiraz is the fifth most populous city in Iran (about 1.9 million in 2016) and lies on a green plain at about 1600 m above sea level. The city supports an oil refinery and various industries in the electronics, manufacturing and agriculture sectors. The climate is moderate semi-arid with an annual average rainfall, humidity and temperature of 335 mm, 64% and 18 ^{o}C, respectively, and the prevailing wind direction is from the northwest. Mount Derak is a sedimentary rock mountain in the Zagros mountain range with a maximum elevation of 2900 m. The climate here is cooler, wetter and less humid than at Shiraz.

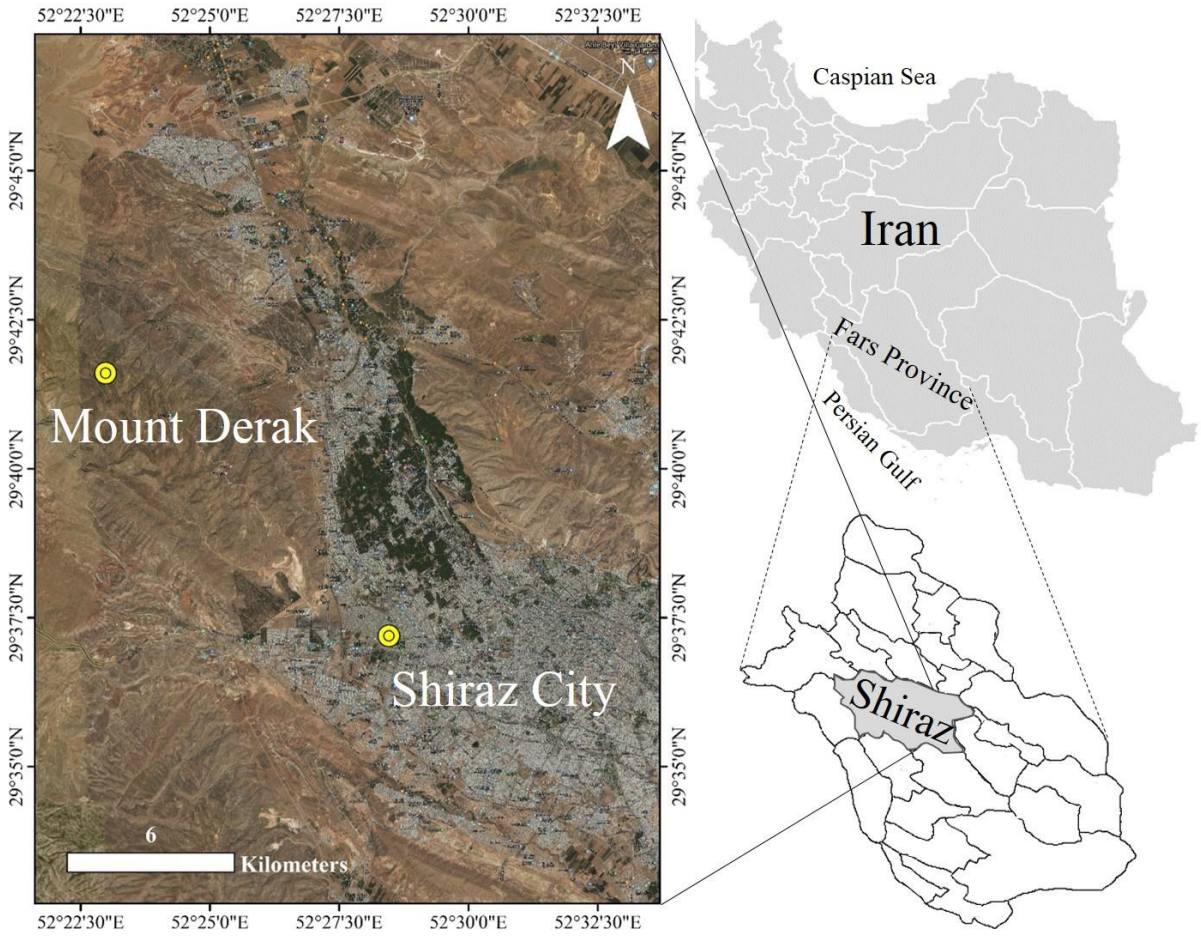


Figure 1: Location of the sampling sites in Shiraz and on Mount Derak.

99

100 *2.2. Sampling*

101 At both locations, dust and precipitation (mainly rainfall) samples were collected from 1 October 2019
102 to 30 September 2020 in customised metallic deposition collectors. To obtain enough material and
103 minimise sample loss during deployment, devices consisted of a wide collection aperture (diameter =
104 35 cm; area = 0.096 m^2) connected to a narrow-necked (~ 2 cm diameter) collection bottle. Specifically,
105 for the collection of dust, the stem of an aluminium foil-wrapped, stainless steel funnel (45^o) was
106 screwed into the neck of a stainless steel bottle, and for the collection of precipitation, the stem of a
107 shallow (10^o), fluted, stainless steel funnel was screwed into the neck of an identical bottle. In Shiraz,
108 the collectors were secured on to the flat roof of a residential building at about 10 m above ground level,
109 while on Mount Derak, collectors were fixed on to an outcrop at about 3 m above ground level.

110 By default, collectors for dust were opened and collectors for rain covered with Al foil. On days when
111 precipitation was forecast (29 occasions throughout the year), dust collectors were manually covered
112 with Al foil and precipitation collectors were uncovered by an operator wearing cotton clothing. At the
113 end of each day with precipitation, or within a few hours after rain had ceased, dust collectors were
114 reopened and precipitation collectors re-covered, after transferring the contents of the latter into a glass
115 jar via a graduated measuring cylinder. At the end of each month, material accumulated in the dust
116 collectors (and including the funnel) was transferred into a clean glass jar the aid of a horse-hair brush
117 and rinsing with filtered water, and between precipitation or dust samples, collector components were
118 cleaned with multiple rinses of filtered (< 2 µm) water. For a more detailed temporal examination of
119 dry and wet deposition of MPs, samples were also taken over a period of ten consecutive days (during
120 March, 2020) consisting of four dry days and six days experiencing precipitation. Monthly or daily
121 meteorological data were obtained from a gauging station located at Shiraz airport, about 7 km to the
122 southeast of the city sampling site.

123

124 *2.3. Sample treatment and microplastic extraction*

In the laboratory, dust samples were transferred to individual glass beakers using a steel spatula and dried for 24 h at 25 ºC in a cleanroom before being weighed and stored in clean, 60 mL glass beakers covered with Al foil. Organic matter in the samples was removed by oxidation with 35 mL of 30% H_2O_2 (Arman Sina, Tehran) until bubble formation ceased. After allowing dust to settle, residual H_2O_2 was decanted and particulate matter washed with deionized water and subsequently dried in a sand bath at 60 °C. MP were isolated by flotation in a saturated solution of $ZnCl_2$ (Arman Sina, Tehran; density 1.6 – 1.8 g cm^{-3}), with the decanted contents centrifuged at 4000 rpm before being filtered through 2 µm pore size S&S filter papers (blue band, grade 589/3). Filters were air-dried at 25 ºC for 48 h in a clean room and transferred to Petri dishes.

2.4. Microplastic counting and characterisation

All MP on each filter were visually identified, counted and characterised under a binocular microscope (Carl-Zeiss, Köln, Germany) at up to 200-x magnification using a 250 µm-diameter stainless steel probe and ImageJ software. Identification and characterisation were based on shape, colour, size, thickness, shininess, hardness and surface structure according to protocols outlined elsewhere and with a size detection limit of about 20 µm (Abbasi et al., 2019). The polymeric construction of 34 MP of a range of shapes, sizes and colours and collected over the ten-day sampling campaign was determined using a micro-Raman spectrometer (µ-Raman-532-Ci, Avantes, Apeldoorn, Netherland) with a laser of 785 nm and Raman shift of 400-1800 cm^{-1}.

2.5. Laboratory cleanliness and quality assurance

Laboratory equipment was washed with phosphate-free soap, double-rinsed with filtered water and soaked in 10% HNO_3 for 24 h before being rinsed twice with double-distilled water, dried at room temperature in a customised clean room and protected by Al foil. Laboratory work surfaces were cleaned with ethanol, laboratory clothing was cotton-based and all reagents and solutions were filtered through 2 µm. Under these conditions, processing of double-distilled water through three blank filters

151 revealed no MP contamination. MP on ten randomly selected dust and precipitation filters were
152 recounted under the microscope for an evaluation of precision and returned the same values as the
153 original counts.

154

155 *2.6. Trajectory modelling and statistics*

156 The potential source range of MP to the study locations was determined from back trajectory frequency
157 using the National Oceanic and Atmospheric Administration online software, Hybrid Single Particle
158 Lagrangian Integrated Trajectory (HYSPLIT), and Global Forecast System (0.25 degree global)
159 meteorological data. Forty eight-hour air mass backward trajectories were calculated from Shiraz at six-
160 hour intervals for each month for a height of 500 m above ground level and at a resolution of 1 degree.

161 Statistical tests were performed using the Data Analysis Tool-Pak in Microsoft Excel 2016 with an α
162 value for significance of 0.05.

163

164 **3. Results**

165 *3.1. Dry deposition of dust and MP*

166 Table 1 shows the mass of settled dust and the number of MP retrieved from dust during each month of
167 the year-long sampling campaign and at both sampling locations along with the corresponding
168 deposition of dust (g per m^2) and the concentration and deposition of MP (per g of dust and per m^2,
169 respectively). Settled dust deposition in Shiraz averages 68.3 g m^{-2} and ranges from 40.6 g m^{-2} in March
170 to 101.9 g m^{-2} in September, and the MP concentration averages 26.4 MP g^{-1} and ranges from 17.2 MP
171 g^{-1} in May to 37 MP g^{-1} in October. Monthly MP deposition averages about 1900 MP m^{-2} and ranges
172 from 822 MP m^{-2} in March to 3494 MP m^{-2} in September, resulting in a total, annual deposition of about
173 23,000 MP m^{-2}. At Mount Derak, monthly dust deposition averages 9.1 g m^{-2} and ranges from 3.1 g m^{-2}
174 in March to 16.6 g m^{-2} in August, and the MP concentration averages 43.2 MP g^{-1} and ranges from
175 31.9 MP g^{-1} in August to 65 MP g^{-1} in April. Monthly MP deposition averages 366 MP m^{-2} and ranges

from 187 MP m^{-2} in February to 582 MP m^{-2} in October, resulting in a total, annual deposition of about 4400 MP m^{-2}. Also shown in Table 1 is the number of MP collected each month from dust samples at Shiraz and Mount Derak that were fibrous in shape. In all cases, fibres of various colours comprised > 95% of MP, with the remaining particles of a fragmented nature. Overall, > 99% of MP sampled were fibrous, whose typical sizes and characteristics are exemplified by the microscopic images in Figure 2.

Table 1: Monthly quantities and concentrations of settled dust and MP at Shiraz and Mount Derak.

	Shiraz						Mount Derak					
Month	dust, g	dust, g m^{-2}	no. MP	no. fibres	MP g^{-1}	MP m^{-2}	dust, g	dust, g m^{-2}	no. MP	no. fibres	MP g^{-1}	MP m^{-2}
October	8.8	91.5	326	321	37.0	3390	1.2	12.5	56	55	46.7	582
November	7.2	74.9	215	213	29.9	2236	1.1	11.4	42	42	38.2	437
December	5.1	53.0	124	123	24.3	1290	0.9	9.4	35	35	38.9	364
January	4.3	44.7	96	96	22.3	998	0.5	5.2	21	21	42.0	218
February	3.5	36.4	84	83	24.0	874	0.5	5.2	18	18	36.0	187
March	3.9	40.6	79	79	20.3	822	0.3	3.1	19	19	63.3	198
April	5.1	53.0	102	101	20.0	1061	0.4	4.2	26	25	65.0	270
May	6.5	67.6	112	110	17.2	1165	0.6	6.2	25	25	41.7	260
June	7.2	74.9	184	184	25.6	1914	0.8	8.3	34	34	42.5	354
July	8.1	84.2	221	219	27.3	2298	1.2	12.5	42	42	35.0	437
August	9.3	96.7	324	323	34.8	3370	1.6	16.6	51	51	31.9	530
September	9.8	101.9	336	333	34.3	3494	1.4	14.6	53	53	37.9	551
mean	6.6	68.3	184	182	26.4	1909	0.9	9.1	35	35	43.2	366
sd	2.2	22.6	100	99	6.4	1038	0.4	4.4	14	14	10.5	142

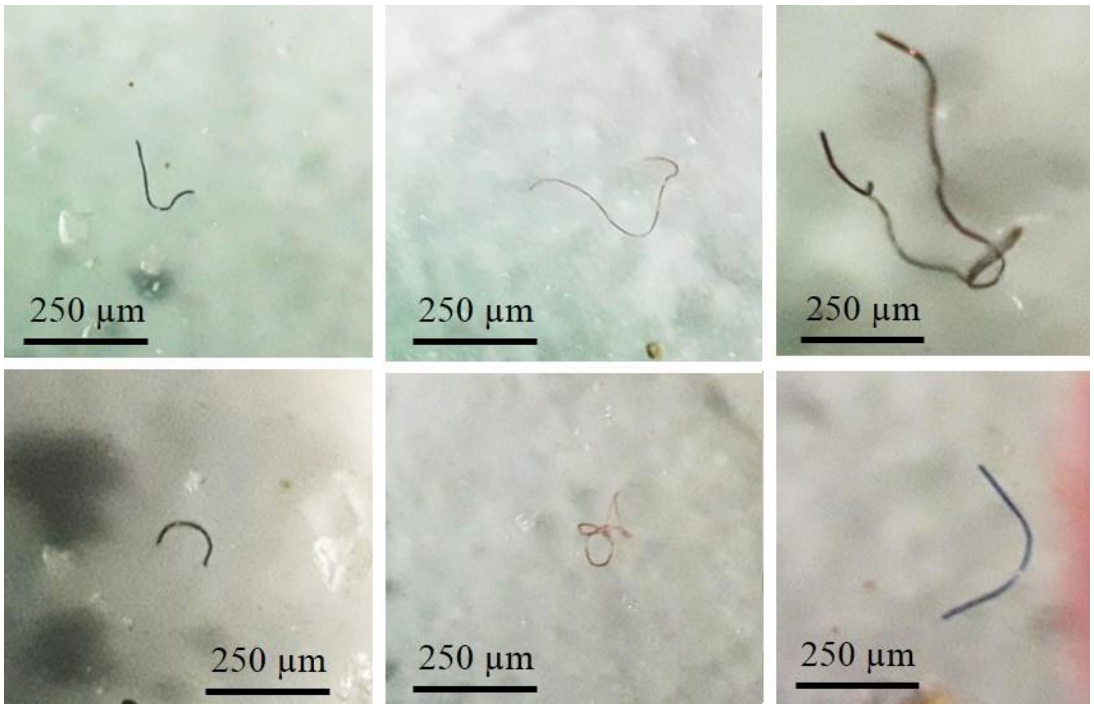


Figure 2: Microscopic images of six fibrous MP retrieved from various settled dust samples.

3.2. Wet deposition of MP

Table 2 shows the results for wet MP deposition, along with gauged precipitation data obtained from Shiraz airport. Precipitation was recorded and collected in days between December and May, with the total number of MP retrieved from Shiraz and Mount Derak ranging from 4 in January to 45 in December and from 1 in January to 9 in December and March, respectively. Monthly MP deposition, also plotted in Figure 2, ranges from about 40 to 470 MP m^{-2} and 10 to 90 MP m^{-2} for Shiraz and Mount Derak, respectively, while total annual wet deposition is about 1150 MP m^{-2} for Shiraz and 350 MP m^{-2} for Mount Derak. When normalised to volume of precipitation, monthly MP concentrations are < 0.4 MP mL^{-1} for Shiraz with the exception of February (about 2.2 MP mL^{-1}) and are < 0.1 MP mL^{-1} for Mount Derak with the exception of February (about 0.7 MP mL^{-1}). Note that, unlike the case for dry deposition, all MPs in precipitation samples retrieved from both locations were fibrous.

Figure 3 compares the monthly dry and wet deposition of MP at the two locations. Overall, dry deposition dominates MP fallout, with wet deposition never contributing more than 30% of total monthly deposition. Annually, wet deposition contributes about 5% and 7% towards total MP deposition at Shiraz and Mount Derak, respectively.

Table 2: Monthly precipitation recorded at Shiraz airport and the volumes of precipitation and concentrations of MP at Shiraz and Mount Derak.

		Shiraz				Mount Derak			
Month	precipitation, mm	volume, mL	no. MP	MP mL^{-1}	MP m^{-2}	volume, mL	no. MP	MP mL^{-1}	MP m^{-2}
October	0	0	0	0	0	0	0	0	0
November	0	0	0	0	0	0	0	0	0
December	73.4	296.4	45	0.15	468	349.5	9	0.03	94
January	12.2	10.5	4	0.38	42	12.3	1	0.08	10
February	5.5	4.5	10	2.22	104	4.4	3	0.68	31
March	57	103.5	21	0.20	218	121.2	9	0.07	94
April	32.7	65.1	17	0.26	177	74.9	7	0.09	73
May	45.5	69.9	14	0.20	146	82.2	5	0.06	52
June	0	0	0	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0
September	0	0	0	0	0	0	0	0	0

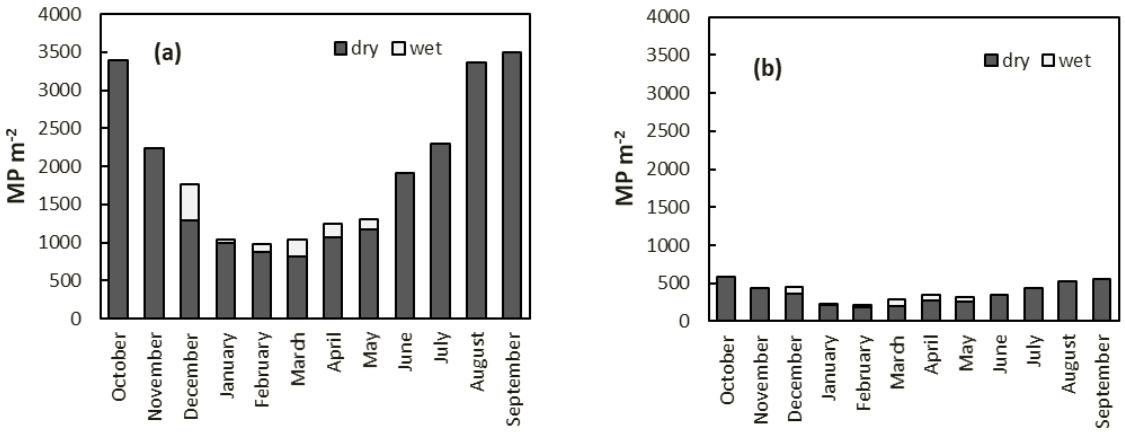


Figure 3: Monthly dry and wet deposition of MP in (a) Shiraz and (b) Mount Derak.

3.3. Size distribution of MP

Figure 4 shows the monthly size distribution of MP in settled dusts and precipitation. In dust samples, the average monthly percentage of the finest fraction of MP (< 100 µm) was significantly greater at Mount Derak (74.6) than in Shiraz (31.8) (p < 0.01 according to an independent t-test). At both locations, the percentage of the finest MP was greatest in late winter (February and March) and lowest in late summer and early autumn (July through to October). A closer examination of the data revealed an inverse relationship between the percentage of fine MP and monthly number of MP (Figure 5). In precipitation, the monthly percentage of the finest fraction of MP exhibited no clear temporal trends. However, average percentages (92.2 at Mount Derak and 83.7 in Shiraz) were significantly greater than the respective average percentages of MP in settle dusts.

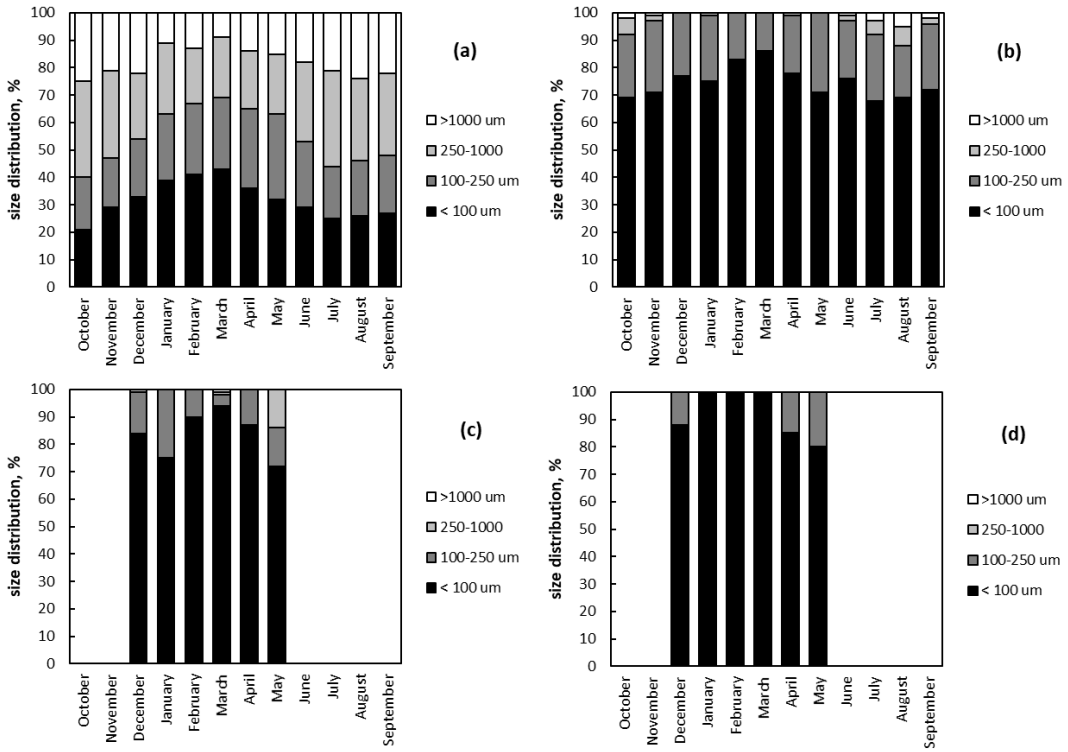


Figure 4: Monthly percentage size distribution of MP in settled dusts from Shiraz (a) and Mount Derak (b) and in precipitation from Shiraz (c) and Mount Derak (d).

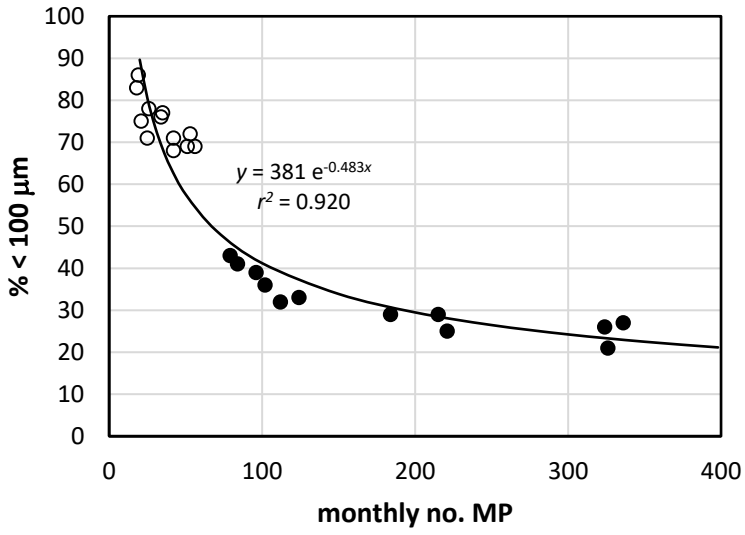


Figure 5: Percentage of MP < 100 µm in length versus monthly number of MP returned for settled dust samples from Shiraz (●) and Mount Derak (o). Annotated is the best-fit line through the data and the equation defining the line.

3.4. Daily MP deposition and polymer type

The volumes of precipitation and numbers of associated MP retrieved on ten successive days of sampling in March are shown in Table 3. The maximum number of MP deposited in a single day was 12 (or about 120 MP m^{-2}), while on two days in Shiraz and four days at Mount Derak no MP deposition was recorded. During spells of continuous precipitation or through successive days in which precipitation occurred, and despite variations in the volume of precipitation sampled, there was a progressive decline in the daily number of MP recorded.

Table 3: Daily volume of precipitation and number of MP recovered from Shiraz and Mount Derak.

	Shiraz		Mount Derak	
day	volume, mL	no. MP	volume, mL	no. MP
1	0	2	0	0
2	0	1	0	1
3	7.5	12	8.2	4
4	7.5	2	9.1	1
5	10.5	0	12.0	1
6	62.1	1	75.1	0
7	0	1	0	0
8	0	3	0	1
9	1.8	3	1.8	1
10	1.5	0	2	0

Figure 6 shows the distribution of MP (n = 34) collected throughout the ten-day sampling period at Shiraz and Mount Derak according to polymer type. Polyolefins and polystyrene are the most abundant polymers and account for 85% of all MP considered and all MP analysed from Mount Derak. Remaining samples from Shiraz were constructed of polyvinylchloride, polyethylene terephthalate and Nylon. Relative polymer abundance also exhibited a significant inverse correlation with material density (r = -0.832; p = 0.05).

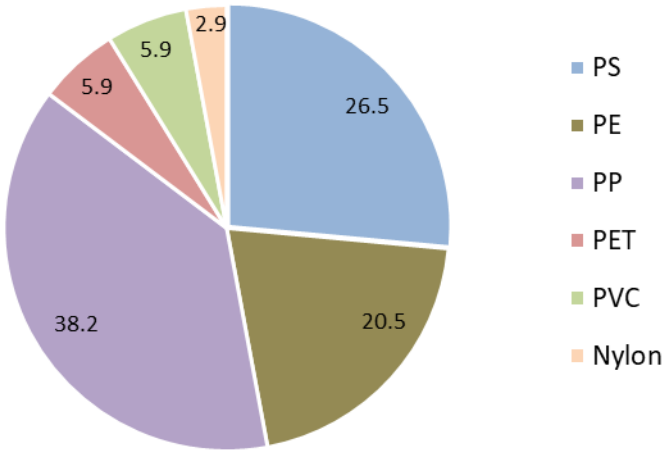


Figure 6: Percentage polymeric distribution of MP (*n* = 34) collected daily from Shiraz and Mount Derak. PS = polystyrene; PE = polyethylene; PP = polypropylene; PET = polyethylene terephthalate; PVC = polyvinyl chloride.

3.5. Monthly trajectory frequencies

Examples of monthly trajectory frequencies at Shiraz, calculated using HYSPLIT for 48-h periods and six-h intervals, are shown in Figure 7. In each month illustrated, the geographical range (exceeding 1% frequency) extends to about 2000 km from the city, and mainly in a northerly or westerly direction. During August and September, when MP deposition (per m^{-2}) was highest and there was no precipitation, the areas of greatest (> 90%) frequency have a dominantly north-westerly or north-easterly component. In contrast, during February and March, when deposition was lowest and precipitation occurred, the areas of greatest frequency have a more southerly component.

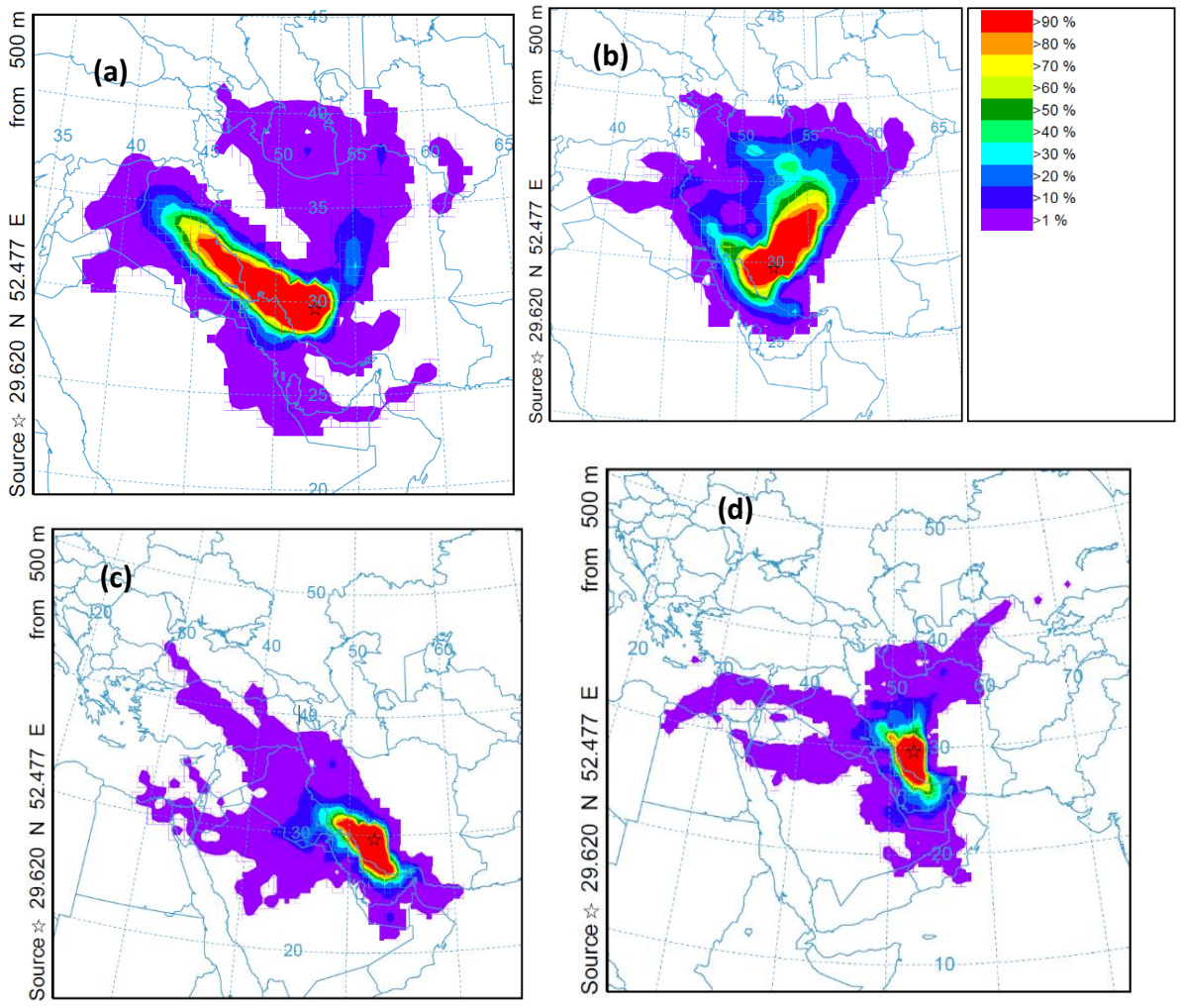


Figure 7: Trajectory frequencies calculated for Shiraz using HYSPLIT over a 48-h period and at six-hourly intervals for (a) August, (b) September, (c) February and (d) March.

4. Discussion

4.1. Spatial variations in dust and MP deposition

The quantities and deposition of dust were considerably greater in the city region of Shiraz than in the remote mountainous region, with differences attributed to the greater abundance and variety of suspendable material in the urban environment (including soil, construction waste, and vehicle- and industrially-emitted particulates). Greater deposition of MP and a higher proportion of relatively large particles in the city setting may be attributed to the proximity of industrial and domestic sources of plastics, and in particular fibrous plastics of polyolefin or PET construction that are typically used in

textiles, furnishings, carpeting and industry (Dris et al., 2017). MP size is also smaller in urban precipitation than in settled urban dust, presumably because (i) larger MP are not readily scavenged or encapsulated by rain drops, and (ii) there exists a higher proportion of smaller, lighter MP that evade gravitational settlement in the higher atmosphere where precipitation is formed or passes. The latter observation is qualitatively consistent with the more general size-deposition distribution of MP shown in Figure 5 and with equivalent distributions illustrated in the recent literature by Bergmann et al. (2019) and Bianco and Passananti (2020). Given such relationships, we predict that where deposition is relatively low, empirical studies of the kind reported here may significantly underestimate MP (and nanoplastic) deposition on a number basis.

Total MP deposition and average particle size are lower at Mount Derak than in Shiraz, consistent with the inverse relationships between size and deposition referred to above. Significantly, however, dry MP deposition normalised to dust mass is greater on Mount Derak than in Shiraz, where the stock of settled and suspendable dusts is augmented by urban anthropogenic sources. Localised sources of deposited MP in the more remote location could include fibres from outdoor gear, clothing and recreational activities (Forster et al., 2020). However, because of the relatively high altitude and prevailing wind directions (see below), we surmise that the majority of particles deposited on Mount Derak reflect the longer-range transportation of fine, low density and low settling velocity MP and their subsequent intersection by the mountain range (see below).

4.2. Temporal variations in MP deposition

In the present study, two climatic seasons (cool and wet: December to May; dry and warm: June to November) were associated with distinctly different patterns of dust and MP deposition at both locations. Thus, the dry season was accompanied by greater deposition of dust per m^{-2} and greater deposition of MP on a number, dust weight-normalised and area-normalised basis. While a significant fraction of material is likely to have been derived locally in Shiraz, trajectory modelling suggests that, on Mount Derak, to the north west of the city and remote from any major population centres and

industries within 100 km in other directions, significant quantities of MP are sourced from urban areas farther afield and transported by regional air masses from the north-west and north-east. Brahney et al. (2020) suggest that the principal source of MP in remote, elevated locations more generally is regional (up to 1000 km) population centres and urban areas further afield that lie on back trajectories of air masses.

During the wet season, dry deposition of MP was augmented by wet deposition, but the total monthly deposition of MP remained lower than that in the dry season (Figure 3). Presumably, this is because as precipitation washes material out from the atmosphere it dampens the ground and inhibits local and regional resuspension of dust and MP. These effects also account for the progressive reduction in MP deposition on successive days of precipitation (Table 3). During this season, trajectory modelling indicates a greater southerly component and a different source of MP in Shiraz and Mount Derak. Regarding the latter, trajectories suggest a significant fraction of MP may be derived directly from Shiraz to the south-east. More generally, air masses from this direction have a greater maritime influence and it is possible that long-range sources could be related to the entrainment of MP from the ocean into the atmosphere through aerosolisation (Allen et al., 2020).

Recent studies in temperate climates have suggested that dry deposition of airborne MP is a significant contributor to atmospheric fallout (Brahney et al., 2020; Roblin et al., 2020; Szewc et al., 2020). The current study confirms that this is also the case for a semi-arid region, with precipitation contributing at most 30% to total monthly deposition and, overall, contributing about 5% and 7% to the annual deposition of MP at Shiraz and Mount Derak, respectively.

4.3. Comparison of dust and MP deposition with previous studies

Monthly quantities of deposited dust in the present study are within the range of values reported for a variety of locations in central Asia by Groll et al. (2013) (< 1 to 700 g m^{-2}) and in the Arabian peninsula by Al-Awadhi and Al Shuaibi (2013) and Engelbrecht et al. (2017) (4 to 320 g m^{-2}). Moreover, the period of maximum dust deposition in Shiraz and Mount Derak (towards the second half of the warm,

dry season and when winds have their greatest northerly component) coincides with the highest monthly accumulations reported for the Arabian coastal zone by Engelbrecht et al. (2017).

Regarding the deposition of MP, comparisons with literature data must be undertaken more cautiously because of differences in sampling periods and designs (for example, wet, dry or combined deposition, elevation above the ground, sampling construction material) and analytical protocols (and in particular means of material digestion, density separation, particle size measurement and particle identification). Thus, some studies report only fibres and neglect other forms of MP (Liu et al., 2020), while other studies do not clearly or quantitatively discriminate natural and synthetic particles or synthetic and petroleum-based particles (Dris et al., 2015; Brahney et al., 2020). The latter approach could be problematic in urban areas where natural or cellulose-based fibres may dominate the pool of deposited fibrous material (Stanton et al., 2019).

With these constraints in mind, total (wet plus dry) monthly numbers of MP deposited in Shiraz and on Mount Derak are compared with the range of values (or mean values) of MP or microfibres reported in the literature in Table 4. Note that where data were reported on a daily or yearly basis, monthly deposition was derived by multiplication by 30 or division by 12, respectively. For Shiraz, MP deposition is the same order of magnitude as total monthly values (after any correction for non-petroleum-based materials) reported for Paris, London, Hamburg and various Chinese cities, but is greater than that reported for Nottingham (UK) and Gdansk (Poland). Total monthly MP deposition at Mount Derak is similar to the mean monthly deposition measured in the remote regions of the South China Sea and the Irish coast, but is lower by more than an order of magnitude than the average monthly deposition of MP reported for other remote, elevated areas, like the Pyrenees, Harburg Hills and protected areas of the USA. Part of the discrepancy may be attributed to the inclusion of natural or synthetic (but non-petroleum-based) fibres amongst the particle cohort and the identification of additional, primary plastic microbeads whose diameters are dominantly < 20 μm and that would not be readily detectable by the methods used in our study (Brahney et al., 2020). Overall, and in both urban and remote areas where polymeric composition has been determined, there appears to be a

heterogeneous assortment of plastics of a range of densities that are suspended in and deposited from the atmosphere.

Table 4: Reports of MP deposition (total, wet or dry) in the literature as minimum, maximum or (in parentheses) mean monthly number per m^2, along with any means of sample digestion and MP separation employed and the principal polymers identified. PE = polyethylene; PP = polypropylene; PS = polystyrene; PET = polyethylene terephthalate; PVC = polyvinyl chloride; PTFE = polytetrafluoroethylene; PA = polyamide; PAN = polyacrylonitrile; EVAC = ethylenevinyl acetate; nd = not determined; ns = not stated.

location	deposition	digestion, separation	min, m^{-2}	max, m^{-2}	% plastic	main polymers	reference
urban							
Paris, France	total	no	870	8400	29	nd	Dris et al. (2015)
Dongguan, China	total	no	5250	9390	23	PE, PP, PS	Cai et al. (2017)
Hamburg, Germany	total	NaClO, Nile Red stain	4080	7830	77	PE, EVAC, PET	Klein and Fischer (2019)
Nottingham, UK	total	H_2O_2	1260	2040	2.3	ns	Stanton et al. (2019)
Six coastal cities, China	total	H_2O_2	2240	7350	100	nd	Liu et al. (2020)
London, UK	total	methanol, Nile Red stain	17,300	30,200	17	PAN, PET, PA	Wright et al. (2020)
Gulf of Gdansk, Poland	total, wet and dry	no	<30	900	100	PET, PP, PE, PVC	Szewc et al. (2020)
Shiraz, Iran	wet and dry	H_2O_2, $ZnCl_2$	978	3490	100	PP, PS, PE	This study
remote							
Harburg Hills, Germany	total	NaClO, Nile Red stain	9940	15,360	77	PE, EVAC, PET	Klein and Fischer (2019)
Protected areas of continental USA	wet and dry	no	1440	13,100	ns	PET, Nylon, PP, PE, PTFE	Brahney et al. (2020)
French Pyrenees	total	H_2O_2, $ZnCl_2$	(11,000)		100	PS, PE	Allen et al. (2020)
South China Sea	total	H_2O_2	(~600)		100	nd	Liu et al. (2020)
Irish Atlantic coast	total and wet	Rose Bengal stain	363	465	100	PET, PAN, PE, PP	Roblin et al. (2020)
Mount Derak, Iran	wet and dry	H_2O_2, $ZnCl_2$	218	582	100	PP, PS, PE	This study

4.4. Environmental and health impacts of airborne MP

The impacts of airborne MP on human health are unclear. Once inhaled, those of the size range identified in the present study are likely to deposited in the upper airways and swallowed into the gut, with those of smaller dimensions but evading detection potentially respirable (Wright et al., 2020). Airborne MP exposure, however, is likely to be far more significant indoors because of the multitude of fibrous and non-fibrous sources of plastic, lack of drivers for dispersion and degradation, and the length of time spent inside (Dris et al., 2017; Gaston et al., 2020; Liu et al., 2020).

The wide dispersion and lengthy residence times of MP and nanoplastics in the atmosphere not only result in global environmental and food-chain contamination (Bergman et al., 2019; Brahney et al., 2020; Roblin et al., 2020) but also have the potential to impact on processes taking place in the atmosphere. For instance, airborne MP and nanoplastics, despite not being hygroscopic, could act as cloud condensing nuclei (Allen et al., 2020). In laboratory studies, Ganguly and Ariya (2019) found

that the ice nucleation efficiency of synthesized polyethylene particles was dependent on various physico-chemical factors, like pH and temperature, and was enhanced in the presence of certain contaminants or natural (e.g. clay) particulates. It is also possible that nucleation efficiency is enhanced by microbiological and photochemical alteration of the plastic surface or through the acquisition of static charge via the triboelectric effect. Since the propensity for airborne MP to act as nucleating agents has implications for climate change, further research in this area is required.

5. Conclusions

MP have been detected and quantified in dry and wet deposition in an urban centre (Shiraz) and a remote, elevated location (Mount Derak) in Iran. Samples were dominated by fibrous particles of polypropylene, polyethylene and PET construction, and monthly deposition exhibited seasonality on both a number and size basis, with more MP and of greater average length deposited during the drier and warmer months. The range of total monthly depositional values (about 1000 to 3500 MP m^{-2} and 200 to 600 MP m^{-2} in Shiraz and at Mount Derak, respectively) and geographical extents of computed back trajectories are comparable with data and model outputs reported in the recent international literature and reinforces the importance of the atmosphere as a vehicle for the global transport of MP. The health and environmental impacts of atmospheric MP remain unclear but warrant further investigation.

Acknowledgements

The authors acknowledge Shiraz University for financial support of the study, and Mr Reza Negarandeh for assistance with sampling at Mount Derak.

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