RESEARCH ARTICLE

Seasonal patterns of microplastics in surface sediments of a Mediterranean lagoon heavily impacted by human activities (Bizerte lagoon, Northern Tunisia)

Takwa Wakkaf[1,2] · Radhouan El Zrelli[3] · Lamia Yacoubi[4] · Mikaël Kedzierski[5] · Yu-Jia Lin[6] · Lamjed Mansour[7] · Stéphane Bruzaud[5] · Lotfi Rabaoui[2]

Abstract

In this paper, we investigated seasonal variations in concentrations of microplastics (MPs) in surface sediments of a lagoon heavily impacted by human activities, located in northern Tunisia (the Bizerte lagoon, southern Mediterranean Sea). Analyses of 112 sediment samples collected from 28 stations between May 2019 and February 2020 revealed significant seasonal variation in concentrations of total MPs, with the highest levels recorded in August 2019 (109.6 ± 59.8 items kg^{-1} DS (dry sediment)) and the lowest in February 2020 (33.2 ± 22.0 items kg^{-1} DS). In terms of polymer types, polyethylene particles were the most abundant throughout the year, followed by polypropylene, polyvinyl chloride, and polyethylene terephthalate. Spatial variations in total MP concentrations were found to depend on several environmental factors, including proximity to the coastline, level of anthropogenic pressure, location inside the lagoon, and presence/absence of vegetation. The upper 5-cm surface sediment layer of the lagoon was found to contain $\sim 9.96 \times 10^{10}$ MP particles, equal to ~ 248.97 t of plastic. Similar patterns of microplastic composition and structure were found throughout the year, revealing the same plastic pollution hotspots during all seasons. This indicates that sources of plastic pollution are land-based and originate from coastal urban, industrial, and agricultural areas, as well as from major freshwater streams. The findings of the present work can help to develop an efficient environmental management plan aiming to reduce and/or stop the spread of plastic pollution and its impacts on the socially and economically important ecosystem of the Bizerte lagoon.

Keywords Plastic pollution · Sediments · Seasonal changes · Human activities · Lagoon · Southern Mediterranean Sea

---

Communicated by Roland Peter Kallenborn.

✉ Lotfi Rabaoui
lrabaoui@gmail.com

1 University of Jendouba, Higher Institute of Biotechnology of Béja, Habib Bourguiba Avenue, 9000 Béja, Tunisia

2 University of Tunis El Manar, Faculty of Science of Tunis, Laboratory of Biodiversity and Parasitology of Aquatic Ecosystems (LR18ES05), 2092 Tunis, Tunisia

3 SADEF, 30 Rue de la Station, 68700 Aspach-Le-Bas, France

4 University of Carthage, Amilcar, Tunis, Tunisia

5 Université Bretagne Sud, IRDL, UMR CNRS 6027, F-56100 Lorient, France

6 National Taiwan University, Institute of Oceanography, Taipei 10617, Taiwan

7 Zoology Department, College of Science, King Saud University, Riyadh, Saudi Arabia

Introduction

Nowadays, plastics are used in a broad variety of applications such as transport, textiles, construction, and packaging (Andrady 2011; Ryan 2015), and they are involved in all aspects of humans' daily life (Thompson et al. 2009). Because of the rapidly increasing demand for plastics since the 1940s, the plastic industry has produced phenomenal quantities of plastics. In fact, it is estimated that total plastic output worldwide increased 20 times over the 50 years from 1964 to 2014 (Neufeld et al. 2016). According to PlasticsEurope (2020), world production of plastics reached 368 million metric tons annually in 2019, and global production continued to expand in spite of increased awareness campaigns and efforts to mitigate plastic pollution (Amelia et al. 2021). Plastic wastes generated in most countries are mismanaged, leading to widespread accumulation of huge quantities of plastics in natural aquatic and terrestrial environments (Woodall et al. 2014;

Jambeck et al. 2015; Geyer et al. 2017). Within this context, Jambeck et al. (2015) estimated that of 275 million metric tons of land-based plastic waste, produced by 192 coastal countries in 2010, between 4.8 and 12.7 million metric tons reached the ocean.

Among seas and oceans worldwide, the Mediterranean Sea is considered the most contaminated with plastics (Lebreton et al. 2012; Eriksen et al. 2014; Suaria et al. 2016). The high concentrations of floating plastics and microplastics in Mediterranean waters are likely to be due to the semi-closed nature of this basin, reduced flows of its surface waters, and increased development of its coasts (Suaria et al. 2016). According to van Sebille et al. (2015), 5 to 10% of the mass of plastics generated globally ends up in the Mediterranean Sea. While numerous studies have been conducted on plastic pollution in northern Mediterranean countries (e.g., Eriksen et al. 2014; Suaria et al. 2016; Kedzierski et al. 2019a, b), similar investigations remain very few along the southern coast (Cózar et al. 2015; Cincinelli et al. 2019), in particular, in coastal lagoons.

The Tunisian coastline contains six coastal lagoons, among which the Bizerte lagoon, located in northern Tunisia, is the most socially and economically important regional body of water (Ksouri and Ben Said 1998; Shaiek et al. 2021). In spite of the species richness and the various fisheries and aquaculture resources characterizing the Bizerte lagoon, this water body has been heavily impacted by various human pressures including urban, agricultural, and industrial activities that generate significant quantities of various pollutants (solids, liquids, and gases), including plastics (Alves Martins et al. 2015; Wakkaf et al. 2020a, b; El Zrelli et al. 2021). A high proportion of the huge masses of domestic waste, including plastics, generated by the urban areas surrounding the lagoon are not managed, and therefore end up in this aquatic system through freshwater streams (Wadis) or wind (Wakkaf et al. 2020b). The huge quantities of plastic waste dumped on its coasts have made it into a huge open plastic dumping site (Wakkaf et al. 2020b). Although some preliminary attempts have been made to study the plastic pollution in the sediments of the Bizerte lagoon, these studies have been very limited and have not covered a sufficient number of stations or taken samples multiple times to sufficiently characterize the environmental issues facing this body of water (Abidli et al. 2017; Toumi et al. 2019). The present work has taken these limitations into account and is intended (*i*) to describe the seasonal variation in the composition, distribution, and abundance of MPs in the surface sediments of the Bizerte lagoon, (*ii*) to identify plastic pollution hotspots and potential sources of pollution in this water system, and (*iii*) to examine the influence of environmental factors on the distribution and abundance of MPs in this transitional water body. The findings of this study represent an important baseline for future monitoring programs of plastic pollution and should help to set up a useful and efficient environmental strategy to reduce and/or stop plastic contamination in this lagoon system.

Material and methods

Study area

The Bizerte lagoon is a transitional Mediterranean water body, located in the North of Tunisia (37°8′–37°14 ′N, 9°46′–9°56 ′E; Fig. 1). It is a 150-km^2 shallow water system with an average depth of 7 m and a maximum depth of 12 m in the channel connecting the lagoon to the open sea (0.3×7 km; Fig. 1). In addition to its connection with the Mediterranean Sea, the lagoon is also connected on its southern side to the freshwater Lake Ichkeul (Fig. 1). This double connection to both marine and freshwater environments makes the Bizerte lagoon system subject to significant seasonal changes, making its waters more saline in summer and less saline in winter, due to alternate increases and decreases in inputs of freshwater from Lake Ichkeul. The ecosystem of the Bizerte lagoon is known for its rich biodiversity, as it hosts many invertebrate and vertebrate species of ecological and/or economic value (Ksouri and Ben Said 1998; Shaiek et al. 2021). In addition, this ecosystem provides various services, in particular, to the fishery and aquaculture sectors (Shaiek et al. 2021). However, in spite of the socio-economic importance of this water body, the Bizerte lagoon has been exposed to various human pressures, represented mainly by the developing urbanization of its coasts, fishing, and establishment of various agricultural and industrial zones around it. Urban and industrial areas are mainly located on either side of the lagoon channel, as well as in the north-eastern (Menzel Abderrahmane and Menzel Jemil) and southern (Menzel Bourguiba) zones. The remaining coastal zones of the Bizerte lagoon contain agricultural areas (on the eastern, southern, and western sides of the lagoon) (Fig. 1). This anthropization has led, during the past decades, to the contamination of the waters and sediments of Bizerte lagoon with various wastes and pollutants, including plastics (Alves Martins et al. 2015; Wakkaf et al. 2020a, b; El Zrelli et al. 2021).

Sediment sampling

To describe seasonal/temporal variation in microplastic content in the surface sediments of the Bizerte lagoon, a total of 112 sediment samples were collected in four sampling surveys, conducted in May, August, and December of 2019, and February of 2020. During each sampling survey, sediment samples were collected from the upper 5-cm surface sediment layer at twenty-eight sampling stations (LB1–LB28, depth range: 1–15 m;
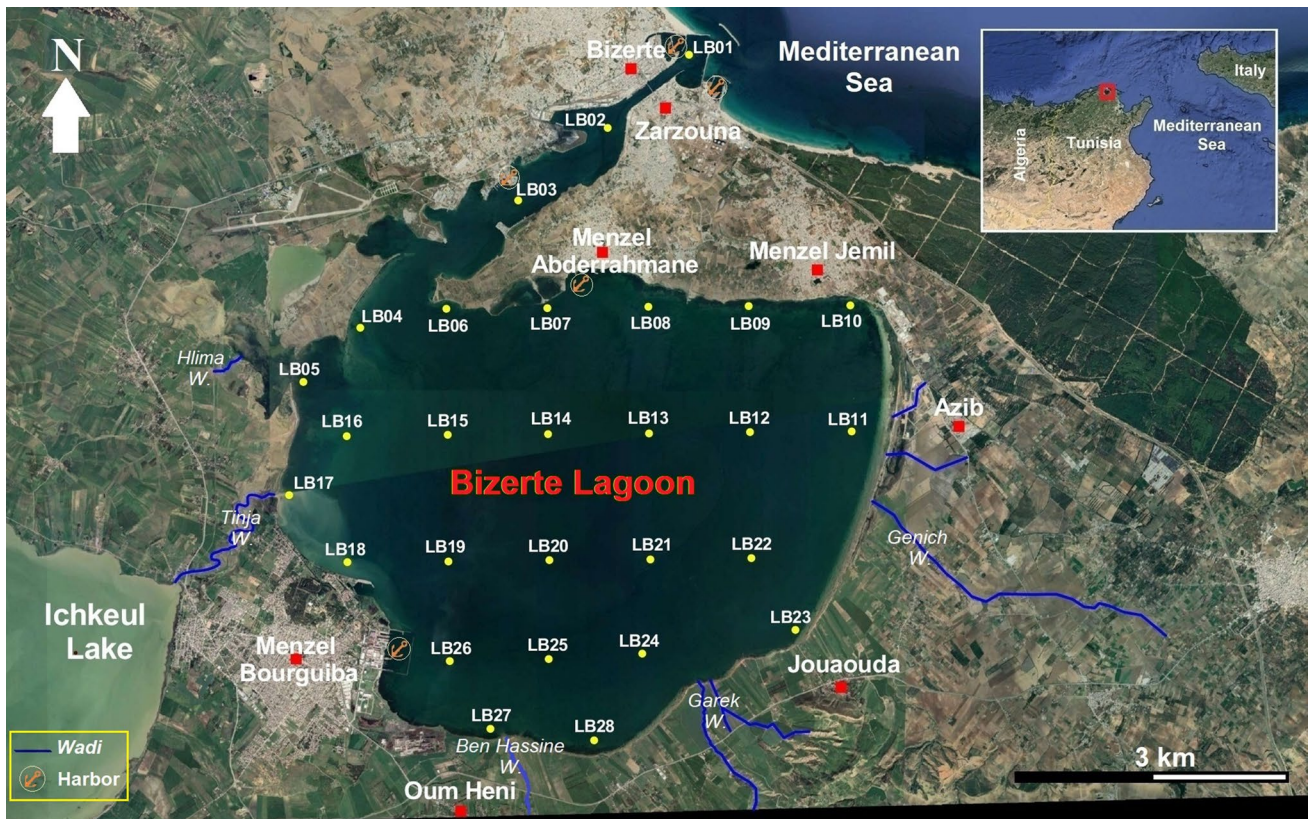
Fig. 1 Locations of the sampling stations of surface sediments in the lagoon of Bizerte (Northern Tunisia). Source: Google Earth (2021)

Fig. 1) by scuba divers, at a rate of one sample per station. At each sampling location, a rectangular $5 \times 25 \times 30$ cm metallic quadrat was placed randomly and sediments were collected using a shovel to a depth of 5 cm. The weight of the collected sediment samples ranged between 650 and 1025 g (average weight = 780 g), but a composite subsample of only 100 g was used from each sediment sample for microplastic analysis. Collected sediment samples were immediately placed in glass jars and transported to the laboratory, where they were stored for further analyses. In parallel with sediment sampling, various environmental variables were recorded at each station, including water depth (m; depth readings were made from the seabed using a depth gauge), presence/absence of vegetated cover (*seagrass*, *algae*, *non-covered*), location inside the lagoon (*lagoon channel*, *northern part of the lagoon*, and *southern part of the lagoon*), proximity to the coastline (*close to the coast*: < 2 km to the nearest coast; *far from the coast*: > 2 km to the nearest coast), distance to freshwater streams (*far*: > 3 km to the nearest freshwater stream, *close*: < 3 km to the nearest freshwater stream), and level of human pressure (*high*, *low*, *average*). In addition, the quantities of rain were estimated for each season, based on the average seasonal records published by the National Institute of Meteorology in Tunisia (NIM, National Institute of Meteorology 2021). Supplementary Table S1 summarizes

details of these environmental factors at each of the sampling stations.

Laboratory analyses

Collected sediment samples were kept in clean stainless-steel trays, covered with perforated aluminum foil sheets, and left to dry in an oven at 40 °C for 48 h (time to reach constant weight). The dried samples were thereafter preserved in sealed glass jars for further analyses.

Microplastic separation from sediment

For each sediment sample, microplastics were extracted using a density separation technique based on sodium iodide (NaI) (Kedzierski et al. 2016). Each sediment sample (100 g) was placed in a 100-mL glass beaker, and NaI solution (1.65 g cm^{-3}) was added, at a rate of 1 *V*/2 *V* (*V*, volume). The samples were thereafter stirred for 2 min. Once the sediment was settled, the solution was filtered three times through a Whatman glass microfiber filter (GGF/C, $\varnothing = 0.45$ μm) to remove any possible contaminants. After being filtered through a sieve of 10 μm of mesh size, a solution of a 30% H_2O_2 was added, and the samples were kept at room temperature for 12 h. The solutions were

thereafter carefully poured through a sieve with a 10-µm mesh. Once filtered, the obtained filters were kept separate, drying in clean film-covered Petri dishes.

Microscopic inspection of microplastics

The plastic materials retained on the meshes were examined under a Leica Zeiss stereomicroscope, following a z-shaped pattern from left to right. Following the standardized protocol described by Frias et al. (2018), microplastics detected in each filter observed were counted and grouped according to their shapes (*fibers*, *films*, and *fragments*) and colors (*clear*, *white*, *blue*, *black*, *red*, *green*, and *yellow*). Some of the microplastic particles were also photographed using a camera connected to the stereomicroscope, and the photos were treated and saved using the Image Motic Plus software. Particles between 300 µm and 5 mm were then selected and transferred in Petri dish for chemical analysis.

Microplastics identification

An attenuated total reflectance Fourier transform infrared spectrometer (ATR-FTIR Vertex70v, Bruker) was used to identify the microplastics separated from each of the sediment samples. Spectra corresponding to the plastic particles detected were registered in absorbance mode, within the 4000–600 cm^{-1} region with a resolution of 4 cm^{-1} and 16 scans. Identification of the microplastics was confirmed through comparison of all obtained spectra with a series of polymer library databases, and the similarity threshold was kept at > 70%. For each microplastic item, a high-quality spectrum was obtained by placing the latter in a germanium diamond cell (ATR Golden Gate). To ensure quality control of the data, we proceeded with cleaning the sample holder with ethanol after each ATR-FTIR analysis. Samples were analyzed per batches of 16 samples, and the sample chamber was cleaned with a vacuum cleaner after finishing from the analysis of each batch. Following the methodology described in Kedzierski et al. (2019b), FTIR spectra were identified using POSEIDON (Plastic pOllutionS ExtractIon, DetectiOn and aNalysis) software.

Prevention of procedural and airborne contamination

During the analyses of samples, all necessary precautions were taken to avoid any procedural or airborne contamination. For instance, complete laboratory analytical process was done in a laminar flow box, and all sediment samples were permanently kept in sealed glass jars. In the laboratory, 100% cotton laboratory coats and gloves were worn, each of which was washed with detergent and thoroughly rinsed with bi-distilled water prior to each phase. All materials and working areas used were thoroughly cleaned with 70% ethanol.

Prior to use, sediment sample containers were also washed with dishwashing liquid and thereafter rinsed with bi-distilled water, and all liquids used were filtered (with a filter of a 1 µm pore size) prior to use. In addition, potential contamination by airborne synthetic fibers was controlled using blanks. The procedural contamination assessed during laboratory analyses was not significant, and therefore did not affect the results of this study.

Statistical data analysis and model interpretation

A generalized linear model using the Poisson likelihood function and natural logarithm link function was applied to analyze the effects of covariates/environmental factors on total MP concentrations. The hypothesis of Poisson distribution was reasonable ($p > 0.95$) for the total MPs, as tested by the *poisson.test* function in R (version 4.0.2, R core team 2020). Possible covariates included anthropogenic pressure levels (*low*, *average*, and *high*), proximity to coastlines and freshwater streams (*close* and *far*), location of stations in the lagoon (*channel*, *northern*, and *southern*), sampling survey (*May 2019*, *August 2019*, *December 2019*, and *February 2020*), substratum type (*muddy*, *sandy*, and *sandy-muddy*), presence/absence of vegetation, water depth (m), and seawater temperature (°C). R package MuMIn (Barton 2020) was applied to construct all possible combinations of the covariates, and the selection between models was made based on the Akaike Information Criterion (AIC): the best model was the one with the lowest AIC value. Once the best model was selected, hierarchical partitioning (Mac Nally and Walsh 2004) was applied to visualize the importance of selected covariates on the indicator of fitting performance, root mean square prediction error. The microplastics were classified into different categories according to three criteria: MP shape (*fibers*, *fragments*, and *films*), MP color (*clear*, *white*, *blue*, *black*, *red*, *green*, and *yellow*), and MP polymer type (*PE*, *PP*, *PVC*, and *PET*), and thus these variables were multivariate. Moreover, multinomial logistic regression was applied to examine effects of the covariates on the proportion of these classifications using the R package *nnet* (Venables and Ripley 2013). The classification reference categories were "*fibers*" for MP shape, "*clear*" for MP color, and "*PE*" for MP polymer type. Models of different combinations of covariates were contrasted with the covariates ranked according to their influence on the total amount of MPs. The model with the lowest AIC value was selected as the best model. In addition, *non-metric* multidimensional scaling was applied to visualize the distribution of the MPs in different colors, using R package *vegan* (Oksanen et al. 2019).

To estimate the total number (MPS$_n$) and mass (MPS$_m$) of microplastic particles in the upper 5-cm surface sediment

layer of the Bizerte lagoon, the following equations were used:

$$MPS_n = M \times (S_L/S_S) \qquad (1)$$

$$MPS_m = MPS_n \times \mathrm{m} \qquad (2)$$

where M, S_s, S_L, and ^{m} are the average concentration of microplastics in the first 5 cm of the lagoon surface sediments per sampling quadrat ($M = [(715$ items $\times 780$ g)$/100$ g]$/112$ quadrats (or samples) $= 49.79$ items/quadrat), the surface area of the sampling quadrat (S s $= 25$ cm $\times 30$ cm $= 750$ cm$^2 = 0.075$ m^2), the surface of the Bizerte lagoon ($S_L = 150\ 10^6$ m^2) and the estimated weight of one MP item ($\mathrm{m} = 2.5 \times 10^{-9}$ t; Wakkaf et al. 2020b), respectively.

Results

MP composition in surface sediments of the Bizerte lagoon

A total of 715 MP particles were identified in the 112 surface sediment samples collected from the Bizerte lagoon during the four seasonal surveys. The highest abundance of MPs (307 particles) was recorded in August 2019, followed by December 2019 (165 particles), May 2019 (150 particles), and February 2020 (93 particles). Table 1 shows the average ($\pm$ SD) concentrations of total MPs estimated in each of the four sampling surveys, with the highest (109.6 ± 59.8 items kg^{-1} DS) and lowest (33.2 ± 22.0 items kg^{-1} DS) values recorded in August 2019 and February 2020, respectively. For the four sampling surveys, the average concentration of MPs was found to be 63.8 ± 30.9 items kg^{-1} DS. Calculations based on Eqs. (2) and (3) showed that the upper 5 cm of the surface sediments of the lagoon was likely to contain $\sim 9.96 \times 10^{10}$ items of MPs, so that a total plastic mass corresponding to ~ 248.97 t. The vast majority of MP particles were fibers which remained in lagoon sediments during the four sampling surveys, with percentages ranging between 57 (December 2019) and 66.7% (February 2020). Plastic fragments and films were found to be less abundant with percentage ranges equal to 25.8–40.6% and 2.4–8.5%, respectively (Supplementary Figure S1-a). In terms of color

composition, the total MPs collected during the four sampling surveys were mostly represented by clear-colored particles, followed by blue-colored and white-colored ones. The other colors (black, red, green, and yellow) were less abundant with green- and yellow-colored MPs occurring the least frequently (Supplementary Figure S1-b). In terms of polymer composition, PE was the prevalent among the four plastic polymer types identified herein (PE, PP, PVC, and PET) in all samples collected during the four sampling surveys with percentages varying from 58.1 (in February 2020) to 72% (in May 2019). PP polymers were the second in abundance, with a percentage varying between 16.7 (in May 2019) and 32.3% (in February 2020), followed by PVC (percentage range: 5.3–7.9%) and PET (percentage range: 4.3–7.3%) polymer particles (Supplementary Figure S1-c). The rate of PE was significantly higher in survey 1 (May 2019) than in surveys 3 (December 2019) and 4 (February 2020). The PP rate was significantly higher in survey 4 (February 2020) compared to surveys 1 (May 2019) and 2 (August 2020). Thus, there was significant variation in the average rates of these two main polymers over time in the Bizerte lagoon. These observations could reflect an increase in the PP/ PE ratio from the dry season to the wet season. No significant seasonal/temporal differences were observed for polymers less dense than 1.0 (i.e., PE, PP) and those denser than 1.0 (i.e., PET, PVC) (Supplementary Table S2).

Spatial variation of MP concentrations in surface sediments of the Bizerte lagoon (all seasons combined)

Figure 2 represents spatial variations of MP concentrations in the surface sediments of Bizerte lagoon, using combined data from all sampling surveys. Whether considering total MPs or separate types of plastic polymers (PE, PP, PVC, and PET), a decreasing pattern of concentrations can be easily observed from the coastal zone to the central area of the lagoon. Highly contaminated areas are located next to urban/industrial areas and some freshwater streams/Wadis (Fig. 2). Average ($\pm$ SD) concentrations (average concentrations of the four sampling surveys) of total MPs and of each of the plastic polymer types identified herein (PE, PP, PVC, and PET) are presented in Supplementary Figure S2 and Supplementary Table S3. Spatial variations in concentrations of PE, PP,

Table 1 Average ($\pm$ standard deviation; SD) concentrations of total microplastics (MPs) in the sediment of the lagoon of Bizerte, estimated for the four sampling surveys

Sampling survey	May 2019 (survey 1)	August 2019 (survey 2)	December 2019 (survey 3)	February 2020 (survey 4)
Average ($\pm$ SD) concentration of total MPs (items kg^{-1} DS)	53.6 ± 40.8	109.6 ± 59.8	58.9 ± 29.7	33.2 ± 22.0

DS, dry sediment

Fig. 2 Spatial variations in the concentrations (items kg. $^{-1}$ DS) of total microplastics (Total) and different plastic polymer types (PE, polyethylene; PP, polypropylene; PVC, polyvinyl chloride; PET, polyethylene terephthalate) in surface sediments of the Bizerte Lagoon during the four surveys combined (May 2019, August 2019, December 2019, and February 2020)
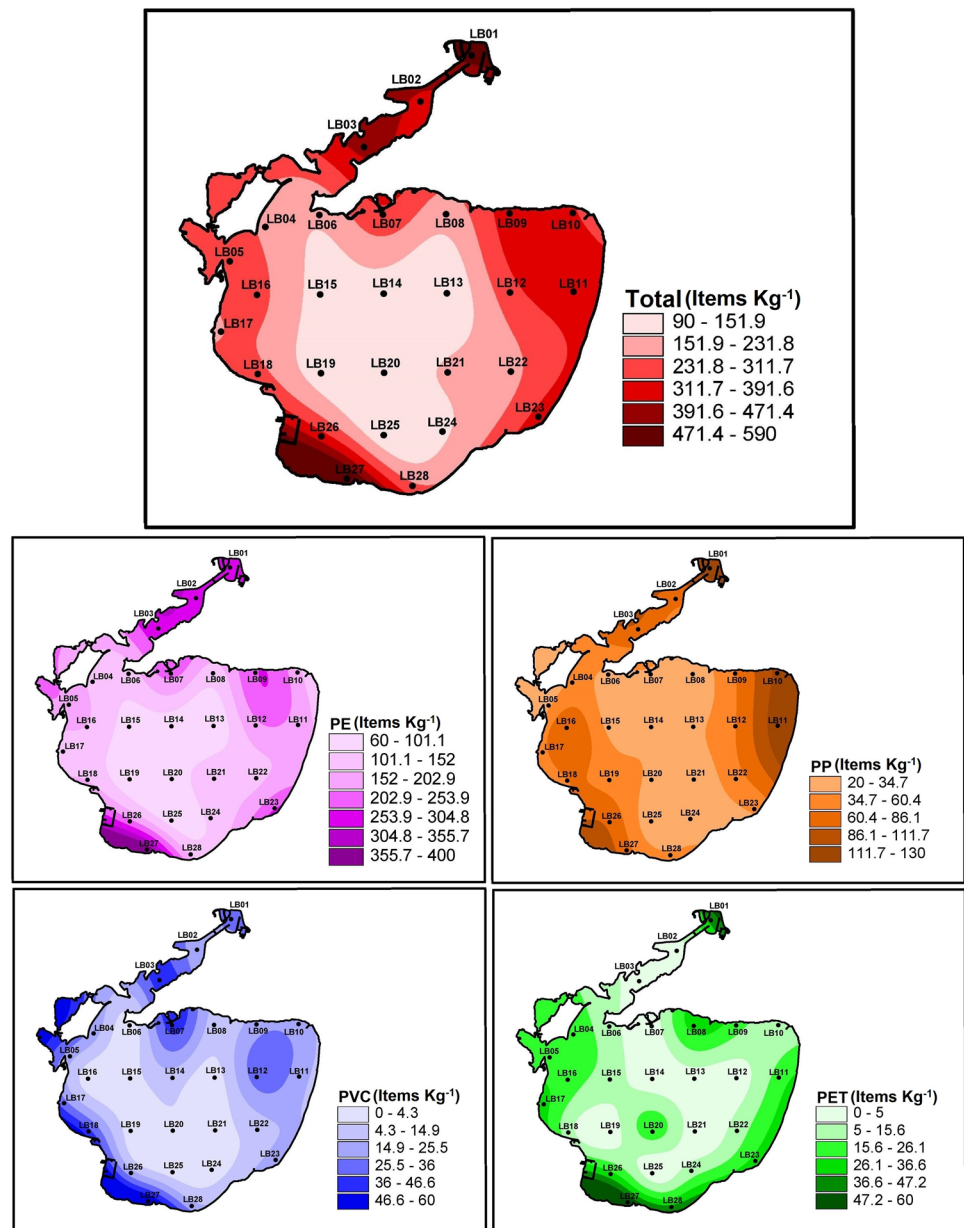
PVC, PET, and total MPs followed the same patterns, showing higher concentrations in those stations sampled close to human-impacted areas. These include stations located between the town of Menzel Bourguiba and Wadi *Ben Hassine* (LB26, LB27, and LB28), those near the town of Jouaouda (LB22 and LB23), those near Wadi *Tinja* (LB16, LB17, and LB18), those located near the towns of Menzel Abderrahmane, Menzel Jemil, and Azib (LB07, LB08, LB09, LB10, LB11, and LB12), and those located in the heavily anthropized channel of the Bizerte lagoon (LB01, LB02, and LB03) (Supplementary Figure S2 and Fig. 1). Low concentrations of MPs were recorded at the other stations (LB04, LB05, LB06, LB13, LB14, LB15, LB19, LB20, LB21, LB24, and LB25) which

occupy the central zone of the main body of the Bizerte lagoon, and are mainly far from the coastal area (Supplementary Figure S2 and Fig. 1).

Seasonal/spatial variations in MP concentrations in surface sediments of the Bizerte lagoon

Spatial variation of sediment MP concentrations in May 2019

In May 2019 (survey 1), clear spatial variations in total microplastics were observed in the lagoon of Bizerte, with the highest concentrations generally in the south, particularly along the coast of the town of Menzel Bourguiba

(stations LB26 and LB27; Fig. 3). The lagoon channel, the eastern coastal area of the lagoon (in front of Menzel Jemil and Azib towns and the freshwater streams from Wadis of *Genich*, *Garek*, and *Ben Hassine*; Fig. 1) also showed higher concentrations compared to the northern and central areas of the main body of this semi-closed aquatic system (stations LB05, LB06, LB13, LB14, LB15, LB16, LB17, LB19, and LB25). Spatial variations in PE concentrations in the surface sediments of the Bizerte lagoon followed the same spatial patterns observed with total MPs. For PP, while the highest concentrations were noted in the channel area and eastern and western coastal areas of the main body of the lagoon, the central area appeared to be less polluted with this polymer type. For PVC and PET, spatial variation inside

the lagoon was similar, showing in general higher contents in the southern part of the Bizerte lagoon, as well as in its channel area (Fig. 3).

Spatial variation of sediment MP concentrations in August 2019

In August 2019 (survey 2), total MPs were found to be much more concentrated in the northernmost part of the Bizerte lagoon channel, as well in the northern, southern, eastern, and western areas, those located near the towns of Menzel Abderrahmane, Menzel Jemil, Azib, and Menzel Bourguiba (Fig. 4). During rainy seasons, these areas are also known to be fed with several streams such as Wadis

Fig. 3 Spatial variations in the concentrations (items kg.$^{-1}$ DS) of total microplastics (Total) and different plastic polymer types (PE, polyethylene; PP, polypropylene; PVC, polyvinyl chloride; PET, polyethylene terephthalate) in surface sediments of the Bizerte Lagoon during May 2019 (survey 1)
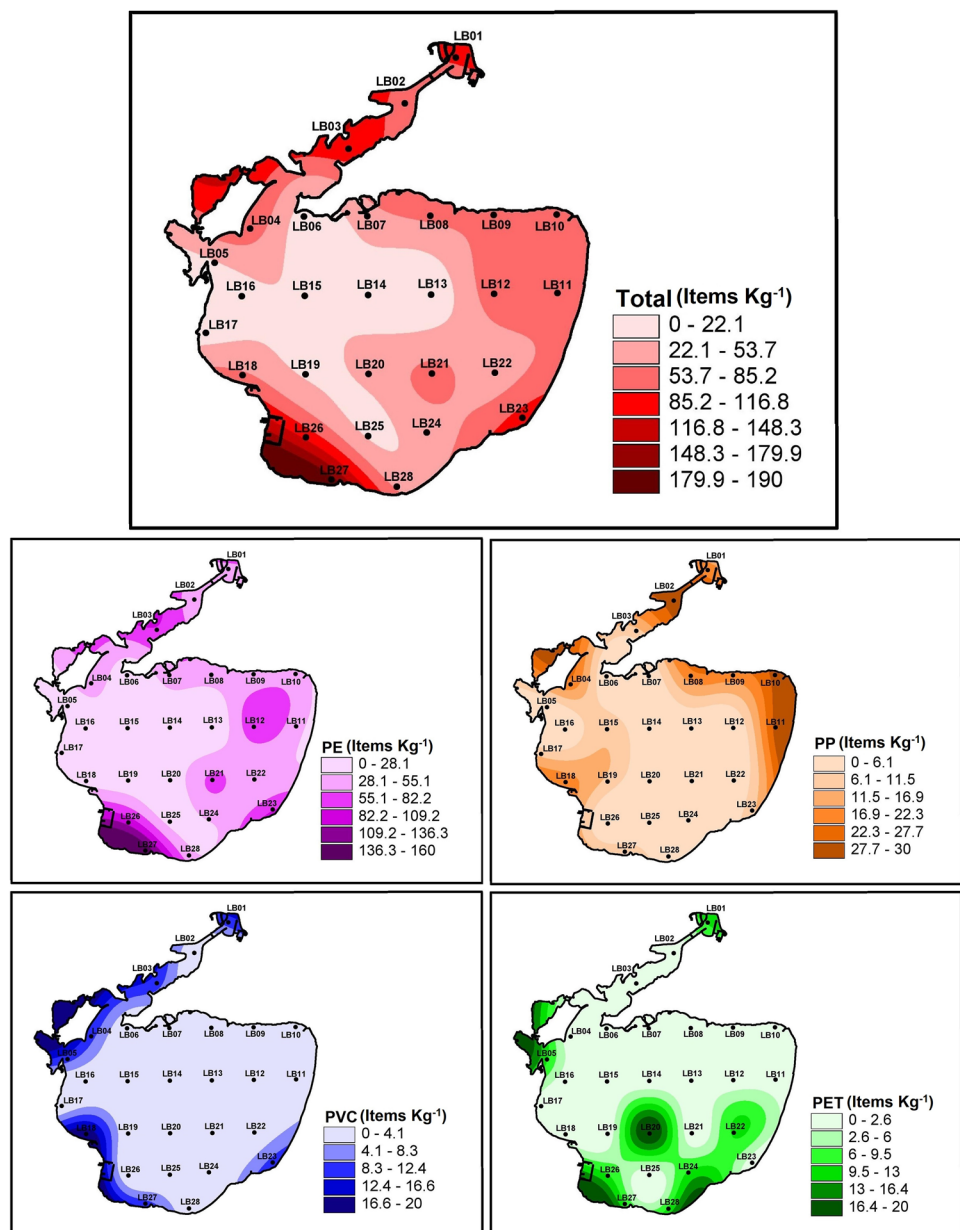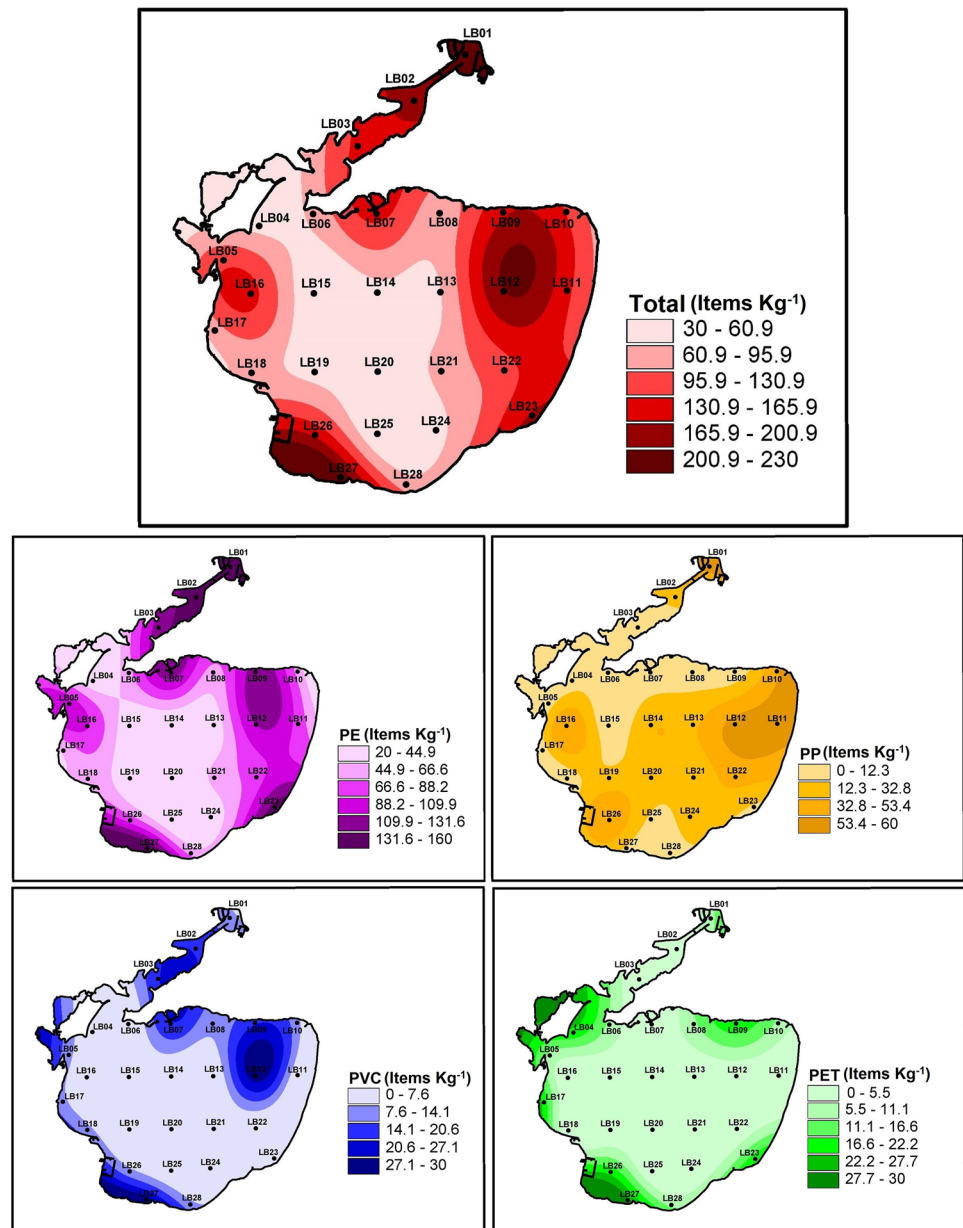
Fig. 4 Spatial variations in the concentrations (items kg.$^{-1}$ DS) of total microplastics (Total) and different plastic polymer types (PE, polyethylene; PP, polypropylene; PVC, polyvinyl chloride; PET, polyethylene terephthalate) in surface sediments of the Bizerte Lagoon during August 2019 (survey 2)


Hlima, *Tinja*, *Ben Hassine*, *Garek*, and *Genich* (Fig. 1). Considering only PE, spatial variation in concentrations of this polymer type was found to follow a very similar pattern to that of total MPs. In the case of PP, the sediments of the Bizerte lagoon showed higher contents in the areas covering the eastern, central, western, and southern parts of this water body. Higher PP concentrations were also detected in the northernmost zone of the lagoon channel. Similar to survey 1 (May 2019), spatial variations of PVC and PET polymers followed similar patterns, showing obvious hotspots near the coastal towns and the urban areas surrounding the lagoon (Fig. 4).

Spatial variation of sediment MP concentrations in December 2019

Although the spatial distribution of total MPs in surface sediments appeared to be much more homogenous in December 2019 (survey 3) compared to surveys 1 and 2 (May 2019 and August 2019, respectively), the lagoon channel area and coastal zones located next to coastal towns and freshwater streams were much more polluted with plastic (Fig. 5). The spatial distribution of PE in the sediments of the Bizerte lagoon followed the same pattern as total MPs, revealing less pollution in the central area of this water body. For PP, some hotspots were

Fig. 5 Spatial variations in the concentrations (items kg. $^{-1}$ DS) of total microplastics (Total) and different plastic polymer types (PE, polyethylene; PP, polypropylene; PVC, polyvinyl chloride; PET, polyethylene terephthalate) in surface sediments of the Bizerte Lagoon during December 2019 (survey 3)
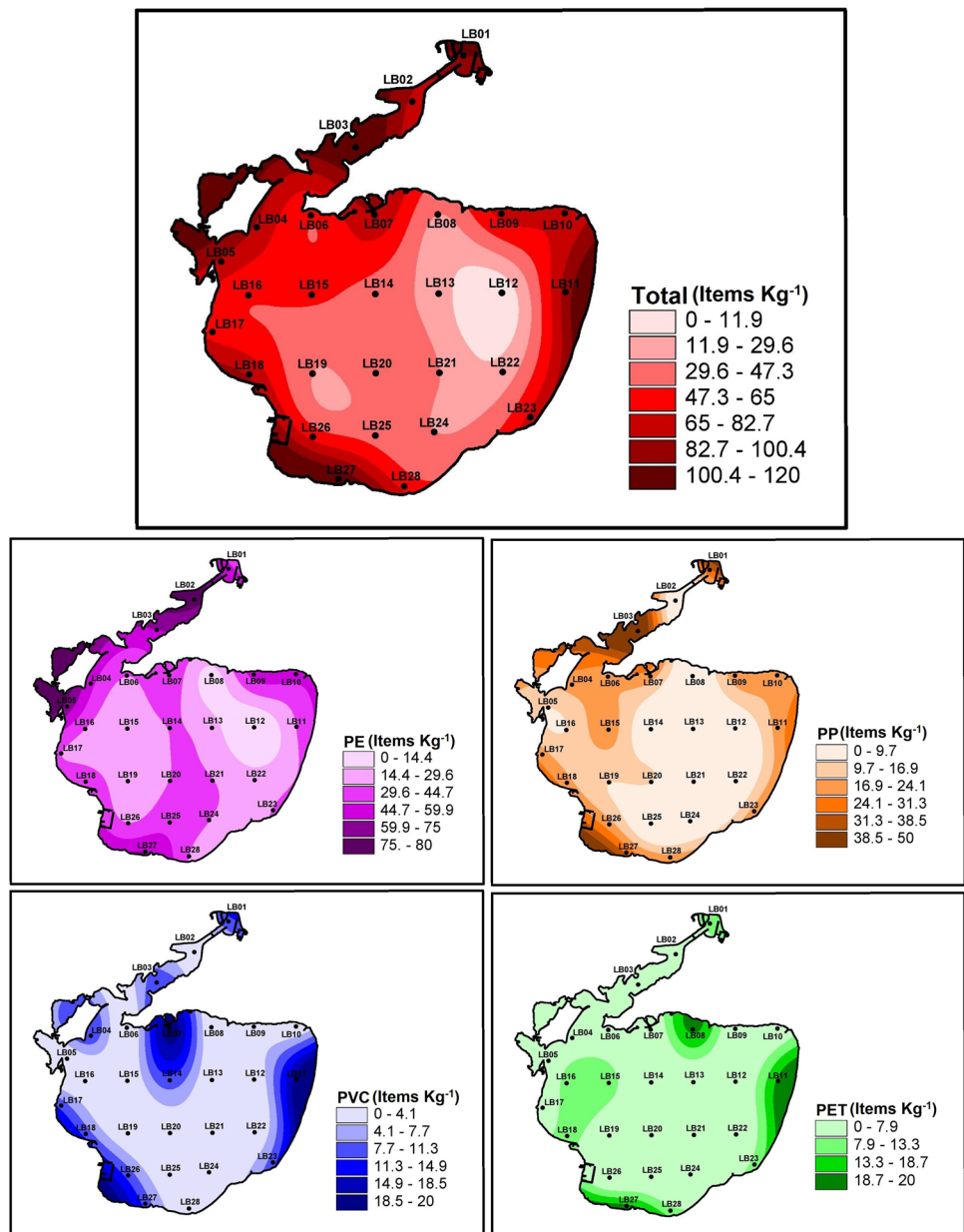
found in the northernmost and central zones of the lagoon channel, as well as in the southern zone along the coast of Menzel Bourguiba town (Fig. 5). High PP contents were also observed in the eastern and northern parts of the lagoon. Similar to the other sampling surveys (May 2019 and August 2019), the same spatial patterns were found for both PVC and PET polymer types, with more or less variation. High concentrations of these polymer types were detected in the lagoon channel, as well as near the towns of Menzel Abderrahmane, Menzel Jemil, Azib, Menzel Bourguiba, and Wadi *Tinja* (Fig. 5).

Spatial variation of sediment MP concentrations in February 2020

In February 2020 (survey 4), the spatial distribution of total MPs showed that all the coastal areas of the Bizerte lagoon were highly polluted with these contaminants, compared to the central area, which appeared to be the least contaminated (Fig. 6). Two main hotspots of total MPs could be observed in the lagoon channel (stations LB01, LB02, and LB03) and in the area located across from Wadi *Tinja* (stations LB05, LB16, LB17, and LB18), connecting the

Fig. 6 Spatial variations in the concentrations (items kg^{-1} DS) of total microplastics (Total) and different plastic polymer types (PE, polyethylene; PP, polypropylene; PVC, polyvinyl chloride; PET, polyethylene terephthalate) in surface sediments of the Bizerte Lagoon during February 2020 (survey 4)
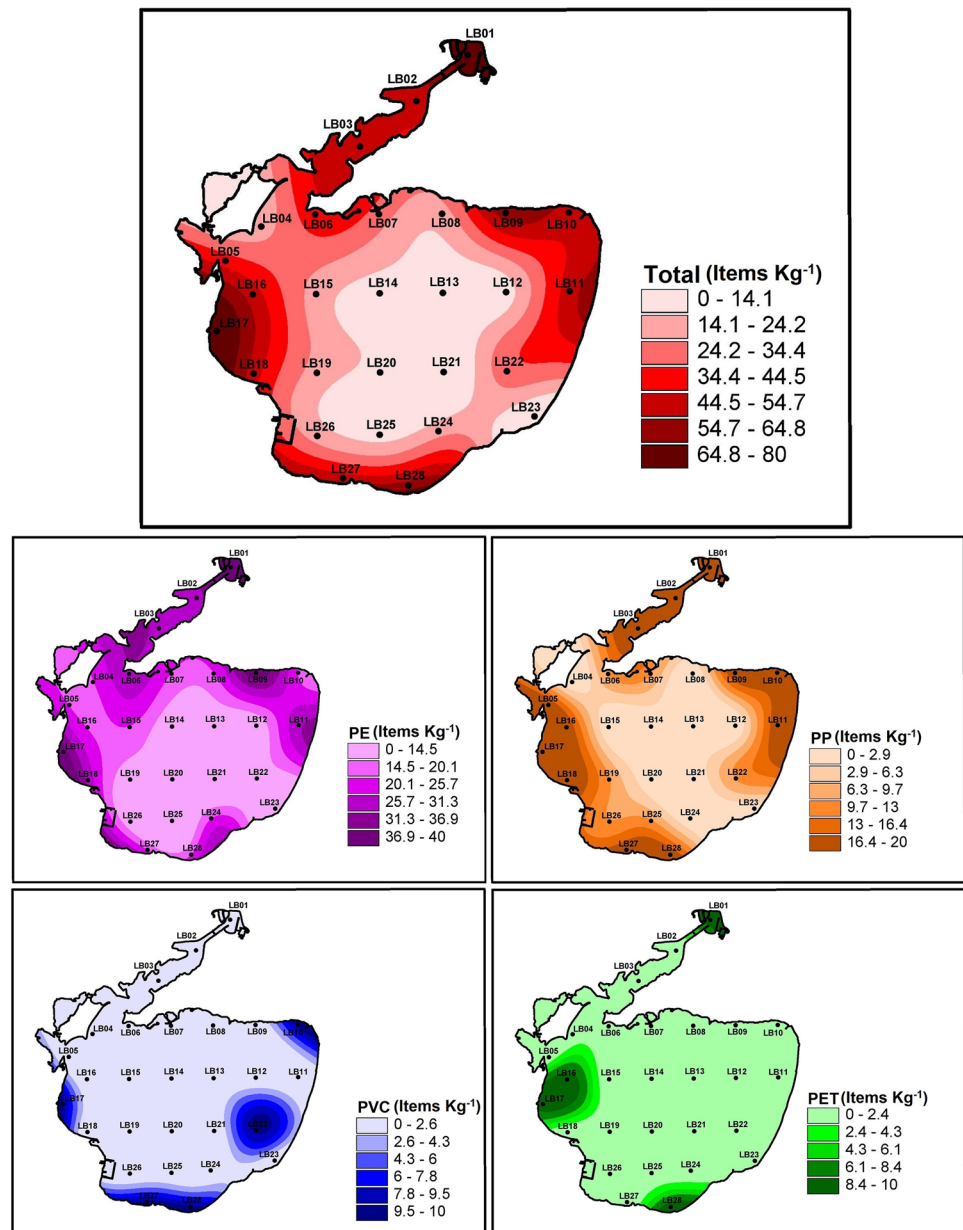
Bizerte lagoon with the freshwater Lake Ichkeul (Fig. 1). Other minor hotspots were also found in the southern and eastern coastal areas of the Bizerte lagoon. Similar to other sampling surveys (May 2019, August 2019, and December 2019), the spatial distribution pattern of PE was very similar to that of total MPs. With PP, while the central area of the lagoon appeared to be less contaminated with this pollutant, some coastal contamination hotspots were detected in the lagoon channel, as well as in the eastern, southern, and western parts of this aquatic system (Fig. 6). Considering PVC polymers, surface sediments of the lagoon were not found to be very contaminated with this plastic polymer type, except for at stations LB10, LB17, LB22, LB27, and LB28. Similar to PVC, the spatial distribution of PET in February 2020

also showed some very localized pollution hotspots in the southernmost (LB28) and westernmost (LB16 and LB17) coastal zones (located near Wadi *Ben Hassine* and Wadi *Tinja*, respectively; Fig. 6).

Effects of environmental factors on the seasonal and spatial distribution of MP concentrations in surface sediments of the Bizerte lagoon

Considering total MP concentrations, the model with "sampling survey," "anthropogenic pressure level," "proximity to the coastline," "location of the station in the lagoon," and "presence/absence of vegetation" factors was the best supported by the data, with the lowest AIC value (Table 2). The

Table 2 Selection of the best model with the total number of microplastics as the response variable and the optimal set of covariates using generalized linear model

P	C_{Coast}	C_{Fresh}	Loc	S	Sub	V	Dep	T	dAIC
+	+		+	+		+			0.00
+	+		+	+		+	+		1.71
+	+		+	+		+		+	1.78
+	+	+	+	+		+			1.97
+	+		+	+	+				1.97
	+		+	+		+			2.13

Covariates included anthropogenic pressure level (P; *low*, *average*, and *high*), proximity to the coastline (C_{Coast}; *close* and *far*) and freshwater streams (C_{Fresh}; *close* and *far*), location of the stations (Loc; *channel*, *northern* or *southern*), sampling survey (S; *May 2019*, *August 2019*, *December 2019*, and *February 2020*), substrate type (Sub; *muddy*, *sandy*, and *sandy-muddy*), presence of vegetation (V), depth in meters (Dep), and temperature in degree Celsius (T). The candidate model with the lowest value of Akaike Information Criterion difference (dAIC) was selected as the best model. + indicates inclusion in the model

Table 3 Coefficient estimates of the best model, and corresponding standard errors (SE) and *p* values

Covariates	Estimates	SE	p
Sampling survey: December 2019	0.095	0.113	0.398
Sampling survey: August 2019	0.716	0.100	**< 0.001**
Sampling survey: February 2020	− 0.478	0.132	**< 0.001**
Proximity to the coastline: *Far*	− 0.565	0.117	**< 0.001**
Location in the lagoon: *Northern*	− 0.538	0.182	**0.003**
Location in the lagoon: *Southern*	− 0.336	0.156	**0.031**
Anthropogenic pressure level: *Average*	0.248	0.101	**0.014**
Anthropogenic pressure level: *High*	0.165	0.166	0.320
Presence/absence of vegetation: *Presence*	0.202	0.097	**0.037**

The reference levels were *May 2019* for sampling survey, *close* for proximity to the coastline, *lagoon channel* for location in the lagoon, *low* for anthropogenic pressure level, *absence* for the presence/absence of vegetation

"sampling survey" factor was the most important covariate, explaining 57% of the root mean square prediction error. "Proximity to the coastline," "anthropogenic pressure level," and "location of the station in the lagoon" factors had similar influences, with 11 to 16% of the root mean square prediction error. The "presence/absence of vegetation" factor had the smallest influence (Supplementary Figure S3). Regarding "sampling survey" effects, MP concentrations were significantly ($p < 0.001$) higher in August 2019 and significantly ($p < 0.001$) lower in February 2020 (Table 3) than in May 2019. Similarly, stations further away from the coastline had significantly lower ($p < 0.001$) concentrations than stations closer to the coastline. Compared to stations in the channel, the stations in the northern and southern areas of the main body of the lagoon had significantly lower MP concentrations ($p = 0.003$ and 0.031 for the northern and southern stations, respectively). Also, stations with average levels of anthropogenic pressure contained significantly higher levels of total MPs ($p = 0.014$) compared to those with lower pressure levels. In addition, stations covered with vegetation showed significantly higher concentrations of total MPs ($p = 0.037$) than those with non-covered sediments (Table 3).

Table 4 shows the process of selecting the best multinomial logistic regression model with different combinations of covariates using AIC as the criterion. Table 5 shows the coefficients and *p*-values of the multinomial logistic regression models. Taking into consideration the composition of different microplastic shapes (i.e., proportions of *fibers*, *fragments*, and *films*) as the response variable, the model considering only the "sampling survey" covariate was found to be the best model, with the lowest AIC value (Table 4). This indicates that the "sampling survey" factor had significant effects on the composition of microplastic shapes. Compared to plastic fibers, fragments occurred more frequently in December 2019 than in May 2019 ($p = 0.056$; Table 5). Considering the composition of microplastic color (i.e., proportions of *clear*, *white*, *blue*, *black*, *red*, *green*, and *yellow* microplastics), the model combining both "sampling survey" and "proximity to coastline" covariates was the most supported by the data, with the lowest AIC value. This indicates that "sampling survey" and "proximity to the coastline" had significant effects on the composition of microplastic color. There were significantly fewer blue microplastics in August 2019 than in May 2019 ($p = 0.001$), significantly fewer red microplastics in December 2019 than in May 2019 ($p = 0.006$), and significantly more green and red microplastics at stations further from the coastline than at stations closer to the coast ($p = 0.002$ and 0.009, respectively; Table 5). Considering the composition of microplastic polymer types (i.e., proportions of *PE*, *PP*, *PVC*, and *PET*) as the response variable, the null model without any covariates was the most supported by the data, with the lowest AIC value (Table 4), indicating therefore that microplastic polymer composition was not affected by any of the covariates tested. The plots of *non-metric* dimensional scaling showing the distribution of total MP-based

Table 4 Selection of the best model for multinomial logistic regression with three types of multinomial response variables (RV): (1) microplastic shape (shape; fiber, fragment, and film), (2) microplastic color (color; clear, white, blue, black, red, green, and yellow), and (3) microplastic polymer (Poly; PE, PP, PVC, and PET) and subset of covariates

RV	S	C_{Coast}	P	Loc	V	Sub	C_{Fresh}	Dep	T	dAIC
Shape	Null									4.39
	+									**0.00**
	+	+								0.64
	+	+	+							5.07
	+	+	+	+						11.92
	+	+	+	+	+					14.65
	+	+	+	+	+	+				15.59
	+	+	+	+	+	+	+			16.10
	+	+	+	+	+	+	+	+		18.14
	+	+	+	+	+	+	+	+	+	21.07
Color	Null									18.44
	+									9.41
	+	**+**								**0.00**
	+	+	+							12.10
	+	+	+	+						15.38
	+	+	+	+	+					21.63
	+	+	+	+	+	+				34.24
	+	+	+	+	+	+	+			39.74
	+	+	+	+	+	+	+	+		35.27
	+	+	+	+	+	+	+	+	+	38.67
Poly	**Null**									**0.00**
	+									5.44
	+	+								4.61
	+	+	+							7.88
	+	+	+	+						12.93
	+	+	+	+	+					15.91
	+	+	+	+	+	+				23.77
	+	+	+	+	+	+	+			27.03
	+	+	+	+	+	+	+	+		29.32
	+	+	+	+	+	+	+	+	+	26.93

The importance of covariates is ranked according to Table 2 and Supplementary Figure S1. The best model is represented by having a dAIC value of 0. *S*, sampling survey; C_{Coast}, proximity to the coastline; *P*, anthropogenic pressure level; *Loc*, location in the lagoon; *V*, presence/absence of vegetation; *Sub*, substratum type; C_{Fresh}, proximity to freshwater streams; *Dep*, water depth (m); *T*, seawater temperature (°C)

Table 5 Coefficients (*p* values between parentheses) of the best multinomial regression model. Those with *p* values <0.05 were marked in bold

Response variable	Sampling survey: *August 2019*	Sampling survey: *December 2019*	Sampling survey: *February 2020*	Proximity to the coastline: *Far*
Microplastic shape (reference = *fiber*)				
Film	0.423 (0.266)	0.629 (0.300)	0.542 (0.550)	
Fragment	0.224 (0.701)	0.242 (0.056)	0.301 (0.622)	
Microplastic color (reference color = *clear*)				
Black	−0.125 (0.756)	−0.235 (0.615)	0.732 (0.116)	0.012 (0.976)
Blue	**−0.899 (0.001)**	−0.295 (0.311)	−0.267 (0.938)	−0.581 (0.074)
Green	−0.918 (0.147)	−9.640 (0.835)	−1.042 (0.353)	**1.888 (0.002)**
Red	−0.761 (0.065)	**−2.136 (0.006)**	−1.277 (0.107)	**1.026 (0.009)**
White	−0.200 (0.505)	−0.044 (0.895)	0.139 (0.725)	0.157 (0.569)
Yellow	−1.307 (0.093)	−9.394 (0.839)	−0.898 (0.429)	0.486 (0.561)

microplastic shapes, colors, and polymer types are shown in Supplementary Figure S4.

Discussion

In spite of the exponential increase in studies on the contamination of marine environments with plastic, there are still few works focusing on this environmental threat on semi-closed environments such as lagoons (Vianello et al. 2013; Mathalon and Hill 2014). Most studies conducted along Mediterranean coasts, including in coastal lagoons, are based on single sampling surveys rather than seasonal sampling, which may help to better understand the dynamics of plastic contaminants on different components of lagoon systems. The present work is the first seasonal and spatial characterization of MPs contaminating surface sediments of the northern Tunisian lagoon of Bizerte. The findings of this work can serve as a model to better understand seasonal dynamics of MPs in lagoons which have been heavily impacted by human activities, especially along the southern Mediterranean coast. The highest concentrations of MPs were recorded in August 2019 and December 2019, which is likely to be due to the agitated status of the lagoon sediments during these months. In fact, it is known that shipping activities inside the lagoon, by both fishermen and visiting tourists, are much more important during these temporal periods (Yahyaoui 2018). This may also be the consequence of increased MP inputs through atmospheric transmission and precipitation during the rainy season, as pointed out by Abbasi et al. (2019) and Dris et al. (2016). Within this context, it is worth noting that atmospheric transport of MPs was reported by various authors to be one of the major modes of transport and delivery of plastic particles to very distant aquatic environments, including deep-sea areas (Zhang et al. 2020).

The interannual variation in the chemical composition of microplastics observed in the surface sediments of the Bizerte lagoon may be linked to the very marked seasonality of water flow of freshwater streams in the Maghreb (Djellouli-Tabet 2010; Varis et al. 2019). In fact, it has been observed that periods of lower freshwater runoff into the Mediterranean have resulted in higher percentages of PE, while periods of intense rainfall led to a decrease in the rate of PE observed on the coast (Gündoğdu et al. 2018). Furthermore, in southern India, where marked seasonality exists, the dry season also results in higher percentages of PE in marine waters than during wet periods (Veerasingam et al. 2016). Thus, the observations of the PP/PE ratio made in our study could reflect a change in chemical composition at the source. In fact, it is possible that in winter, plastics lying on land are carried toward the lagoon by runoff, leading to a higher increase of PP than during the summer (Gündoğdu

et al. 2018). It is also interesting to note that in May and December, months for which the number of microplastics collected are comparable, the distribution of microplastic density in the sediments of the Bizerte lagoon does not show the same pattern. Indeed, microplastics collected in May seem to be distributed near the coast. This pattern could be explained by a lower propagation of microplastics, perhaps linked to a lower rate of flow by freshwater streams feeding into the Bizerte lagoon. In December, on the contrary, microplastics seem to be more widely dispersed and could therefore be attributed to a higher rate of flow by these streams.

The average concentration of MPs estimated in the sediments of the Bizerte lagoon (63.8 ± 30.9 items kg^{-1} DS; range: 33.2–109.6 items kg^{-1} DS) was found to be within the range of concentrations reported in the sediments of other continental and lagoon environments. The overall average MP concentration estimated herein was far below those recorded in other Mediterranean and Atlantic lagoons and estuaries such as the Venice lagoon, Italy (1445.2 items kg^{-1} DS; Vianello et al. 2013); the intertidal ecosystem surrounding Halifax Harbor, Canada (4100 items kg^{-1} DS; Mathalon and Hill 2014); and in the north-east Atlantic Ocean (421 items kg^{-1} DS; Maes et al. 2017). It was, however, far higher than the concentrations recorded in the Tyrrhenian Sea (1.7 items kg^{-1} DS; Mistri et al. 2020) and the intertidal plain of the Northeast coast of Brazil (3.5 items kg^{-1} DS; Costa et al. 2011) (Table 6). Harris (2020) reported that the median concentration of MPs in the sediments of estuarine and lagoon environments, based on the results of 19 studies, reaches ~300 items kg^{-1} DS, which is nearly five times higher than the average concentration of MPs in the sediments of the Bizerte lagoon. This can be explained by the effects of several environmental factors, including the type of sediments (sandy, muddy, or sandy-muddy), tidal and wave activity, and level of coastal anthropization (Harris 2020). This can also be explained by the different size ranges targeted in the various studies conducted around the globe. Compared to tide-dominated and wave-dominated estuarine and deltaic environments, lagoon environments exhibit higher median concentrations of MPs in their sediments (~800 MP items kg^{-1} in lagoons versus ~150 and ~300 MP items kg^{-1} in tide-dominated and wave-dominated estuarine and deltaic environments, respectively; Harris 2020). The high concentration of MPs in lagoon sediments is likely to be due to their sediment trapping efficiency, which is higher for lagoons and wave-dominated estuaries than for tide-dominated environments (Harris and Heap 2003). Moreover, the concentrations of MPs in surface sediments were reported to correlate with grain size (Maes et al. 2017; Mu et al. 2019). Unfortunately, in our study, we did not measure sediment grain size to test the correlation of this variable to MP concentrations, although some previous studies found

Table 6 Comparison of average concentrations of microplastics (MPs; items kg.$^{-1}$ DS) in surface sediments and their ranges (given between parentheses) from different regions around the globe

Sea	Region (country)	Lagoon/estuary	Average MP concentrations in surface sediments (items kg^{-1} DS)	Reference
Mediterranean Sea	Bizerte lagoon (Tunisia)	Lagoon	63.8 (33.2–109.6)	*Present study*
Mediterranean Sea	Venice Lagoon (Italy)	Lagoon	1445.2 (672–2175)	Vianello et al. (2013)
Mediterranean Sea	Piombino channel (northern Tyrrhenian Sea)	Estuarine	1.70 (0.43–4.0)	Mistri et al. (2020)
Atlantic Ocean	Intertidal ecosystem surrounding Halifax Harbor (Nova Scotia, Canada)	Lagoon	4100 (2000.0–8000.0 according to tide level)	Mathalon and Hill (2014)
Atlantic Ocean	Northeast coast of Brazil	Estuarine	3.5	Costa et al. (2011)
Atlantic Ocean	North-East Atlantic (Belgium, UK, France, and Netherlands)	Estuarine	421.0 (0–3146)	Maes et al. (2017)

no statistically significant relationship between these two variables (Mathalon and Hill 2014; Nor and Obbard 2014; Peng et al. 2017; Alves and Figueiredo 2019).

Similar to other studies on MPs in the sediments of lagoon environments (Mathalon and Hill 2014; Sruthy and Ramasamy 2017), fibers were identified as the most common type of MPs in the sediments of the Bizerte lagoon, with high percentages varying between 57.0 and 66.7% throughout the year. In contrast, our records were far higher than those found by Vianello et al. (2013) in the Venice lagoon (Italy; only 10%). According to Harris (2020), the prevalence of fibers in sediments depends on the nature/type of marine environment. While fibers dominate more in beach (median value = 90%) and deep-sea environments (median value = 75%), they are less common in wave-dominated estuaries and shelves (median value = 70%), tide-dominated shelves (median value = 63%), shallow coastal environments (median value = 61%), and tide-dominated estuarine systems (median value = 49%) (Harris 2020). Khatmullina and Isachenko (2017) attributed the prevalence of fibers in sediments to their enhanced buoyancy (due to their high surface area to mass ratio), which seems to facilitate their concentration on beaches and in coastal areas such as lagoons. Since plastic fibers are known to be derived mainly from washing clothes and domestic wastewater (Browne et al. 2011; Napper and Thompson 2016), their prevalence in the sediments of the Bizerte lagoon indicates that the intensive domestic wastes imposing on this aquatic system have not been controlled. It is worth mentioning that concentrations of microplastics were also found to depend on the presence/absence of vegetation. Sediments covered with algae and/or seagrass were found to retain many more microplastics. This is in agreement with the findings of other studies highlighting the role of vegetated coastal habitats as sinks for plastics (Martin et al. 2020).

Our results made it possible to define plastic pollution hotspots in the lagoon of Bizerte. These are located mainly next to developed areas along or near the coast. These hotspots are limited to the zones exposed to coastal urban, industrial, and agricultural areas (the lagoon channel; areas next to the towns of Menzel Bourguiba, Menzel Abderrahmane, Menzel Jemil, Azib, and Jouaouda; and areas opposite to freshwater streams/Wadis such as Wadi *Tinja* and Wadi *Ben Hassine*; Fig. 1). The same plastic pollution hotspots were identified during all seasons, indicating that the sources of plastic contamination posing on the Bizerte lagoon are the same throughout the year, and that microplastic inputs from atmospheric transmission and precipitation (rain) are minor compared to land-based sources. This does not match with the findings of Wang et al. (2021), who noted seasonal variations in the contents of MPs in the Manas River Basin, China, related to seasonal changes in atmospheric transmission and precipitation. These regional variations could be explained by variability of anthropogenization and coastal development in the two studied areas, as well as variability in the efficiency of plastic waste management. Along its coast, the Bizerte lagoon is known to host several urban, industrial, and agricultural complexes that generate significant quantities of plastic waste, much of which ends up in the waters and/or sediments of this water body (Wakkaf et al. 2020b). According to the 2010 report of the Tunisian Agency for the Promotion of Industry and Innovation (APII 2010), many plastic-producing (and/or by-producing) industries, such as shoe/textile factories, plastic and tire factories, food industry appliance factories, and electrical/electronics factories, have been located along the coast of the lagoon. Significant quantities of plastic waste produced by these factories or generated by adjacent urban and agricultural areas are likely to contaminate the aquatic environment of the Bizerte lagoon. The plastic pollution problem seems to be intensified

by the absence of an efficient management process for the discharge of pollution in the region of Bizerte (Wakkaf et al. 2020b). For instance, significant quantities of diverse kinds of meso-, macro-, and megaplastics encountered along the coastal area of the Bizerte lagoon indicate that domestic wastes (including plastics) are not well managed in this region (Fig. 7) and that many uncontrolled points of discharge exist in the areas surrounding the lagoon (Wakkaf et al. 2020b). These unmanaged/uncontrolled plastic waste can easily be transported by wind or runoff into the aquatic system of the Bizerte lagoon. Because of unmanaged plastic waste, plastic pollution is quite common in the marine environment in many non-developed countries (Garcia et al. 2019; Cordova and Nurhati 2019).

The total number of MP particles and mass contained in the upper 5 cm layer of surface sediments in the Bizerte lagoon (9.96×10^{10} particles; ~248.97 t) was found to be ~6 times higher than that estimated in the upper 25-cm layer of surface waters in the same lagoon (16.99×10^{9} items; 42.47 t; Wakkaf et al. 2020b). This proves that the sediments of the lagoon act as a sink for plastics. Trapping of microplastics in the sediments seems to be enhanced by various environmental factors, including the properties of the sediment (mostly muddy and sandy in the lagoon), trapping of plastics by vegetation (seagrass and algae), and low hydrodynamics in the lagoon. All these factors are likely to contribute to mechanic and sedimentary trapping of plastic particles.

This finding leads to the deduction that the vegetated cover of the lagoon sediments will continue to degrade and regress because of the continuous input of pollutants (industrial, agricultural, and urban wastes; El Zrelli et al. 2021), which is likely to lead to the remobilization of sediment-trapped MPs and exacerbate the impact on the fragile ecosystem of the Bizerte lagoon. Moreover, climate change represented mainly by torrential rains in the region is likely to lead to severe changes in the current spatial distribution of MPs and flux between water and sediment compartments (due to an increase in MP flux and higher hydrodynamics in the lagoon). It is also possible that the aquatic plants and algae covering the sediments of the Bizerte lagoon could be affected by climate change and that they might not be able to adapt to an increase in temperature, with serious consequences on their survival and on the retention of MPs in the sediments. Thus, it is extremely urgent to take action immediately to enact an efficient program to manage the sources of plastic pollution in the Bizerte lagoon. Otherwise, the future scenarios of the distribution and abundance of plastic pollution in this aquatic system may depend on other uncontrollable parameters, such as climate change and the gradual suspension of MPs trapped in sediment.

Fig. 7 Photos showing some of the unmanaged/uncontrolled plastic waste observed along the coast of the Bizerte lagoon

Conclusion

The present work endeavored to study the seasonal patterns of microplastic contents in the surface sediments of the Bizerte lagoon (northern Tunisia), a Mediterranean lagoon heavily impacted by human activities, and to identify plastic pollution hotspots in this aquatic system. The concentrations of total MPs varied significantly between the four sampling surveys, with the highest levels recorded in August 2019 (109.6 ± 59.8 items kg^{-1} DS) and the lowest in February 2020 (33.2 ± 22.0 items kg^{-1} DS). In contrast to the observed temporal changes in the concentrations of total MPs, plastic polymer composition was not found to differ significantly among the sampling surveys. Spatial variations in the concentrations of MPs did not vary significantly in the lagoon by sampling survey, with the highest records in the same zones throughout the year. Pollution hotspots were located mainly in coastal zones subjected to human pressures (urban, industrial, and agricultural complexes), but also in areas of major runoff and inflow of freshwater streams/Wadis. The most significant sources of plastic pollution contaminating the lagoon of Bizerte are land-based, indicating a clear problem of uncontrolled and/ or unmanaged plastic waste in the region. The findings of the present work represent an important baseline for future monitoring of plastic pollution in the Bizerte lagoon and can help decision makers to adopt an efficient environmental management plan aiming to reduce the impact of plastic pollution in this lagoon. Developing and executing such an environmental management plan is extremely urgent to reduce the hazardous impacts of plastic contaminants on local fauna and humans and to ensure the sustainability of natural resources related to the aquatic system of the Bizerte lagoon. The key steps toward the success of any environmental management strategy should focus on (*i*) setting up an efficient management plan of domestic wastes (including plastic); (*ii*) banning uncontrolled domestic waste dumping sites, in particular in the plastic pollution hotspots identified in this work; and (*iii*) reducing the flow of plastic wastes from surrounding freshwater streams.

Author contribution TW: samples and data collection, data analysis, writing - original draft preparation. REZ and MK: conceptualization, methodology, supervision, writing—reviewing and editing. LY, and LM: methodology, resources, writing—reviewing and editing. SB and LR: conceptualization, methodology, resources, investigation, supervision, project administration, funding acquisition, writing—reviewing and editing.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interest The authors declare no competing interests.

References

Abbasi S, Keshavarzi B, Moore F, Turner A, Kelly FJ, Dominguez AO, Jaafarzadeh N (2019) Distribution and potential health impacts of microplastics and microrubbers in air and street dusts from Asaluyeh County. Iran Environ Pollut 244:153–164

Abidli S, Toumi H, Lahbib Y, Trigui El Menif N (2017) The first evaluation of microplastics from the complex Lagoon-Channel of Bizerte (northern Tunisia). Water Air Soil Pollut 228:262

Alves VEN, Figueiredo GM (2019) Microplastic in the sediments of a highly eutrophic tropical estuary. Mar Pollut Bull 146:326–335

Alves Martins MV, Zaaboub N, Aleya L, Frontalini F, Pereira E, Miranda P, Mane M, Rocha F, Laut L, El Bour M (2015) Environmental quality assessment of Bizerte lagoon (Tunisia) using living foraminifera assemblages and a multiproxy approach. PLoS ONE 10(9):e0137250

Amelia TSM, Khalik WMAWM, Ong MC, Shao YT, Pan H-J, Bhubalan K (2021) Marine microplastics as vectors of major ocean pollutants and its hazards to the marine ecosystem and humans. Prog Earth Planet Sci 8:12. https://doi.org/10.1186/s40645-020-00405-4

Andrady AL (2011) Microplastics in the marine environment. Mar Pollut Bull 62:1596–1605

Browne MA, Crump P, Niven SJ, Teuten E, Tonkin A, Galloway T, Thompson R (2011) Accumulation of microplastic on shorelines worldwide: sources and sinks. Environ Sci Technol 45:9175–9179

Cincinelli A, Martellini T, Guerranti C, Scopetani C, Chelazzi D, Giarrizzo T (2019) A potpourri of microplastics in the sea surface and water column of the Mediterranean Sea. TrAC-Trend Anal Chem 110:31–326

Cordova MR, Nurhati IS (2019) Major sources and monthly variations in the release of land-derived marine debris from the Greater Jakarta area. Indonesia Sci Rep 9:18730

Cózar A, Sanz-Martin M, Marti E, Ganzalez-Gordillo JI, Ubeda B, Galvez JA, Irigoien X, Duarte CM (2015) Plastic accumulation in the Mediterranean Sea. PLoS ONE 10(4):e0121762

Dris R, Gasperi J, Saad M, Mirande C, Tassin B (2016) Synthetic fibers in atmospheric fallout: a source of microplastics in the environment? Mar Pollut Bull 104(1–2):290–293

El Zrelli R, Yacoubi L, Wakkaf T, Castet S, Grégoire M, Mansour L, Courjault-Radé P, Rabaoui L (2021) Surface sediment enrichment with trace metals in a heavily human-impacted lagoon (Bizerte Lagoon, Southern Mediterranean Sea): Spatial distribution, ecological risk assessment, and implications for environmental protection. Mar Pollut Bull 169:112512

Eriksen M, Lebreton LCM, Carson HS, Thiel M, Moore CJ, Borerro JC, Galgani F, Ryan PG, Reisser J (2014) Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. PLoS ONE 9:e111913

Garcia B, Fang MM, Lin J (2019) Marine plastic pollution in Asia: all hands on deck! Chin. J Environ Law 3:11–46

Geyer R, Jambeck JR, Law KL (2017) Production, use, and fate of all plastics ever made. Sci Adv 3:e1700782

Gündoğdu S, Çevik C, Ayat B, Aydoğan B, Karaca S (2018) How microplastics quantities increase with flood events? An example from Mersin Bay NE Levantine coast of Turkey. Environ Pollut 239:342–350. https://doi.org/10.1016/j.envpol.2018.04.042

Harris PT (2020) The fate of microplastic in marine sedimentary environments: a review and synthesis. Mar Pollut Bull 158:111398

Harris PT, Heap AD (2003) Environmental management of coastal depositional environments: inferences from an Australian geomorphic database. Ocean Coast Manag 46(5):457–478

Jambeck JR, Geyer R, Wilcox C, Siegler TR, Perryman M, Andrady A, Narayan R, Law KL (2015) Plastic waste inputs from land into the ocean. Science 347:768–771

Kedzierski M, Villain J, Falcou-Prefol M, Kerros ME, Henry M, Pedrotti ML, Bruzaud S (2019) Microplastics in Mediterranean Sea: a protocol to robustly assess contamination characteristics. PLoS ONE 14:e0212088

Kedzierski M, Falcou-Prefol M, Kerros ME, Henry M, Pedrotti ML, Bruzaud S (2019) A machine learning algorithm for high throughput identification of FTIR spectra: application on microplastics collected in the Mediterranean Sea. Chemosphere 234:242–251

Khatmullina L, Isachenko I (2017) Settling velocity of microplastic particles of regular shapes. Mar Pollut Bull 114(2):871–880

Ksouri J, Ben Said R (1998) Potentialités en macroalgues : cartographie et biomasse de l'agarophyte *Gracilaria* dans le lac de Bizerte. Bull Inst Nation Sci Technol Mer 25:17–34

Lebreton L, Greer S, Borrero J (2012) Numerical modeling of floating debris in the world's oceans. Mar Pollut Bull 64:653–661

Mac Nally R, Walsh CJ (2004) Hierarchical partitioning public-domain software. Biodivers Conserv 13(3):659

Mathalon A, Hill P (2014) Microplastic fibers in the intertidal ecosystem surrounding Halifax Harbor. Nova Scotia Mar Pollut Bull 81(1):69–79

Mistri M, Scoponi M, Granata T, Moruzzi L, Massara F, Munari C (2020) Types, occurrence and distribution of microplastics in sediments from the northern Tyrrhenian Sea. Mar Pollut Bull 153:111016

Mu J, Qu L, Jin F, Zhang S, Fang C, Ma X, Zhang W, Huo C, Cong Y, Wang J (2019) Abundance and distribution of microplastics in the surface sediments from the northern Bering and Chukchi Seas. Environ Pollut 245:122–130

Napper IE, Thompson RC (2016) Release of synthetic microplastic plastic fibres from domestic washing machines: effects of fabric type and washing conditions. Mar Pollut Bull 112(1–2):39–45

Nor NHM, Obbard JP (2014) Microplastics in Singapore's coastal mangrove ecosystems. Mar Pollut Bull 79(1):278–283

Peng G, Zhu B, Yang D, Su L, Shi H, Li D (2017) Microplastics in sediments of the Changjiang Estuary. China Environ Pollut 225:283–290

Shaiek M, El Zrelli R, Crocetta F, Mansour L, Rabaoui L (2021) On the occurrence of three exotic decapods, *Callinectes sapidus* (Portunidae), *Portunus segnis* (Portunidae), and *Trachysalambria*

palaestinensis (Penaeidae), in northern Tunisia, with updates on the distribution of the two invasive portunids in the Mediterranean Sea. BioInvasions Rec 10(1):158–169. https://doi.org/10.3391/bir.2021.10.1.17

Sruthy S, Ramasamy EV (2017) Microplastic pollution in Vembanad Lake, Kerala, India: the first report of microplastics in lake and estuarine sediments in India. Environ Pollut 222:315–322

Suaria G, Avio C, Mineo A, Lattin GL, Magaldi MG, Belmonte G, Moore ChJ, Regoli F, Aliani S (2016) The Mediterranean plastic soup: synthetic polymers in Mediterranean surface waters. Sci Rep 6:37551

Toumi H, Abidli S, Bejaoui M (2019) Microplastics in freshwater environment: the first evaluation in sediments from seven water streams surrounding the lagoon of Bizerte (Northern Tunisia). Environ Sci Pollut Res 26:14673–14682

van Sebille E, Wilcox Ch, Lebreton L, Maximenko N, Hardeesty BD, van Franeker JA, Eriksen M, Siegel D, Galgani F, Law KL (2015) A global inventory of small floating plastic debris. Environ Res Lett 10:124006

Varis O, Taka M, Kummu M (2019) The planet's stressed river basins: too much pressure or too little adaptive capacity? Earth's Future 7:1118–1135. https://doi.org/10.1029/2019EF001239

Veerasingam S, Mugilarasan M, Venkatachalapathy R, Vethamony P (2016) Influence of 2015 flood on the distribution and occurrence of microplastic pellets along the Chennai coast. India Mar Pollut Bull 109:196–204. https://doi.org/10.1016/j.marpolbul.2016.05.082

Wakkaf T, El Zrelli R, Kedzierski M, Balti R, Shaiek M, Mansour L, Tlig-Zouari S, Bruzaud S, Rabaoui L (2020a) Microplastics in edible mussels from a southern Mediterranean lagoon: preliminary results on seawater-mussel transfer and implications for environmental protection and seafood safety. Mar Pollut Bull 158:111355

Wakkaf T, El Zrelli R, Kedzierski M, Balti R, Shaiek M, Mansour L, Tlig-Zouari S, Bruzaud S, Rabaoui L (2020b) Characterization of microplastics in the surface waters of an urban lagoon (Bizerte lagoon, Southern Mediterranean Sea): Composition, density, distribution, and influence of environmental factors. Mar Pollut Bull 160:111625

Wang G, Lu J, Li W, Ning J, Zhou L, Tong Y, Liu Z, Zhou H, Xiayihazi N (2021) Seasonal variation and risk assessment of microplastics in surface water of the Manas River Basin. China Ecotoxicology and Environmental Safety 208:111477

Woodall LC, Sanchez-Vidal A, Canals M, Paterson GL, Coppock R, Sleight V, Calafat A, Rogers AD, Narayanaswamy BE, Thompson RC (2014) The deep sea is a major sink for microplastic debris. R Soc Open Sci 1:140317. https://doi.org/10.1098/rsos.140317

Zhang Y, Kang S, Allen S, Allen D, Gao T, Sillanpää M (2020) Atmospheric microplastics: a review on current status and perspectives. Earth Sci Rev 203:103118

APII (Agence de Promotion de l'Industrie et de l'Innovation), 2010. Les Industries du Textile et d'Habillement en Tunisie. Agence de Promotion de l'Industrie et de l'Innovation, Ministère de l'Industrie et de la Technologie, Monographie, Tunis. Tunisia. (42 pp).

Barto K, (2020). MuMIn: Multi-Model Inference. R package version 1.43.17. https://CRAN.R-project.org/package=MuMIn.

Costa MF, Silva-Cavalcanti JS, Barbosa CC, Portugal JL, Barletta M 2011 Plastics buried in the inter-tidal plain of a tropical estuarine ecosystem. J. Coast. Res. 64, 339–343 (Proceedings of the 11th International Coastal Symposium ICS2011).

Djellouli-Tabet Y 2010. Common scarcity, diverse responses in the Maghreb Region BT - water and sustainability in arid regions: bridging the gap between physical and social sciences, in: Schneier-Madanes, G., Courel, M.-F. (Eds.). Springer

Netherlands, Dordrecht, pp. 87–102. https://doi.org/10.1007/978-90-481-2776-4_6

Frias J, Pagter P, Nash R, O'Connor I, Carretero O, Filgueiras A, Viñas L, Gago J, Antunes J, Bessa F, Sobral P, Goruppi A, Tirelli V, Pedrotti ML, Suaria G, Aliani S, Lopes C, Raimundo J, Caetano M, Palazzo L, de Lucia GA, Camedda A, Muniategui S, Grueiro G, Fernandez V, Andrade J, Dris R, Laforsch Ch, Scholz-Böttcher BM, Gerdts G 2018 Standardised protocol for monitoring microplastics in sediments. JPI-Oceans BASEMAN project. 23 pp.

Google Earth. 2021. Lagoon of Bizerte, 37°11'57.55''N, 9°52'38.25''E, Alt. 25.32 km. SIO, NOAA, U.S. Navy, NGA, GEBCO. Maxar Technologies 2020, viewed 21 April 2021.

Kedzierski M, Le Tilly V, César G, Sire O, Bruzaud S 2016 Efficient microplastics extraction from sand. A cost effective methodology based on sodium iodide recycling. Mar. Pollut. Bull. 115 (1–2), 120–129.

Maes T, Van der Meulen MD, Devriese LI, Leslie HA, Huvet A, Frère L, Robbens J, Vethaak AD 2017 Microplastics baseline surveys at the water surface and in sediments of the North-East Atlantic. Front. Mar. Sci. 4 (135).

Martin C, Baalkhuyur F, Valluzzi L, Saderne V, Cusack C, Almahasheer H, Krishnakumar PK, Rabaoui L, Qurban MA, Arias-Ortiz A, Masqué P, Duarte CM 2020 Exponential increase of plastic burial in mangrove sediments as a major plastic sink. Sci. Adv, 6 (44), eaaz5593.

Neufeld L, Stassen F, Sheppard R, Gilman T (2016) The new plastics economy — rethinking the future of plastics. World economic forum, Ellen MacArthur Foundation, McKinsey & Company http://www.ellenmacarthurfoundation.org/publications

NIM, National Institute of Meteorology, 2021. Meteorological data of Bizerte 2019/2020.

Oksanen J, Blanchet FG, Friendly M, Kindt R, Legendre P, McGlinn D, Minchin PR, O'Hara RB, Simpson GL, Solymos P, Henry M, Stevens MHH, Szorecs E, Wagner H (2019) vegan: Community Ecology Package. R package version 2.5–6. https://CRAN.R-project.org/package=vegan

PlasticsEurope. 2020. Plastics - the Facts 2020. An analysis of European plastics production, demand and waste data. PlasticsEurope, Association of Plastics Manufacturers [https://www.plasticseurope.org/download_file/force/4261/181].

R Core Team., 2020. R: A language and environment for statistical computing. Version 4.0.2. R foundation for statistical computing, Vienna, Austria. https://www.R-project.org/.

Ryan, P.G. 2015. A brief history of marine litter research. In: Marine anthropogenic litter, ed. Bergmann, M., Gutow, L. and Klages, M. Springer, Cham, 2015, pp. 1–25.

Thompson, R.C., Swan, S.H., Moore C.J., vom Saal, F.S. 2009. Our plastic age. Philos. Trans. R. Soc., B, 364, 1973–1976.

Venables WN and Ripley BD 2013. Modern applied statistics with S-PLUS. Springer Science & Business Media.

Vianello, A., Boldrin, A., Guerriero, P., Moschino, V., Rella, R., Sturaro, A., Da Ros, L., 2013. Microplastic particles in sediments of Lagoon of Venice, Italy: first observations on occurrence, spatial patterns and identification. Estuar. Coast. Shelf Sci. 130, 54e61.

Yahyaoui A 2018. Conflits d'usage environnementaux sur les rives de la lagune de Bizerte (Tunisie), une mise en perspective méditerranéenne. PhD Thesis, Aix-Marseille Université, France. 443 pp.