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Review

Microplastics pollution in different aquatic environments and biota: A review of recent studies

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ABSTRACT

Microplastics (MPs) are generated from plastic and have negative impact to our environment due to high level of fragmentation. They can be originated from various sources in different forms such as fragment, fiber, foam and so on. For detection of MPs, many techniques have been developed with different functions such as microscopic observation, density separation, Raman and FTIR analysis. Besides, due to ingestion of MPs by wide range of marine species, research on the effect of this pollution on biota as well as human is vital. Therefore, we comprehensively reviewed the occurrence and distribution of MPs pollution in both marine and freshwater environments, including rivers, lakes and wastewater treatment plants (WWTPs). For future studies, we propose the development of new techniques for sampling MPs in aquatic environments and biota and recommend more research regarding MPs release by WWTPs.

1. Introduction

Plastic materials are relatively young materials with history about 60 years. Then, they have covered almost all aquatic environments (Van Cauwenberghe et al., 2013; Gündoğdu and Çevik, 2017). Modern concern about MPs has been growing since 2004 as Thompson studied on ocean plastic at Plymouth University in the United Kingdom. They found MPs in most of the samples from 18 British beaches, as well as in plankton samples collected from the North Sea as far back as the 1960s (Thompson et al., 2004).

With the increasing world population, the usage of plastic has increased, meanwhile the waste management of plastics is still concern for researchers. As reported by Plastics*Europe* (2017), about 335 million tonnes of plastics were produced in the year 2016. This increased production is a cause for concern about the ecological consequences of ingested plastic and potential MPs pollution. There is a question to how widely MPs have affected aquatic environments and their biota (Villarrubia-Gómez et al., 2017; Xanthos and Walker, 2017).

There is no significant attention to the MPs pollution terrestrial ecosystems like urban environment in comparison to the marine ecosystem (Dehghani et al., 2017). In fact, the level of MPs pollution is higher in undeveloped areas due to lack of proper waste management which may cause huge amount of plastics to enter from land to oceans by 2025 (Jambeck et al., 2015).

Plastics can be classified in three size classes of large MPs (1 to < 5 mm), mesoplastics (5 to < 25 mm) and macroplastics (≥25 mm) (Lee et al., 2013). In terms of type MPs have been fallen into five groups: fragments (hard, jagged-edged particles), micro-pellets (hard, rounded particles), fibers (fibrous or thin uniform plastic strands), films (thin, 2-dimensional plastic films), and foam (i.e., Styrofoam-type material) as reported by Anderson et al. (2017). Although, they can divided in six basic types as polyethylene (PE), polypropylene (PP), polyamide (PA), polyvinyl chloride (PVC), polystyrene (PS), polyurethane (PUR), and polyethylene terephthalate (PET) (Hidalgo-Ruz et al., 2012; Van Cauwenberghe et al., 2015a; Pitt et al., 2018). According to Peters et al. (2017), fragments are the least commonly ingested form of MPs while they are generated from MP degradation. Degraded MPs and weathered polymer-based particles have ranges between 50 and 5000 μm in size and are available in marine, freshwater, and estuarine environments (Peters and Bratton, 2016). Table 1 shows the size, shape and color of different types of MPs in some studies.

Based on this introduction, the objectives of this review were

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Table 1
Comparison of different types of MPs in terms of physical appearance.

Type	Size	Shape	Color	Composed group
Fragment		Chips/swarf	Different colors	Dominant group
Film	< 0.1 mm	Hard and flat	Different colors	Not common
Foam	0.1 mm diameter	Elongated and thin shape, spongy texture	White/yellow	Usually PS and PE
Plastic pellets	0.25–0.5 mm,	Spherical	White/gray	Microbeads
	1–2 mm,	Cylindrical	Colorless/translucent	PE
Fibers	Thickness of 30 μm,	Rounded	White/transparent	All size fractions

Adopted from: (Kunz et al., 2016; Van der Hal et al., 2017).

divided to several parts as follows: (1) MPs pollution in different aqueous environments such as fresh waters (lake and rivers), marine and wastewater treatment plants (2) Evaluation of MPs pollution in biota and (3) Suggestion of strategies and methods to reduce the MPs effect based on existing gaps.

2. Source of micro-plastics

Source identification of MPs sources is crucial to reducing the social, environmental and economic impacts (Pettipas et al., 2016). The source of MPs can be categorized as primary such as pellets and secondary which resulting from the fragmentation of larger plastics. Besides, the classification of sources can be as land-based e.g. litter, microbeads and sea-based e.g. fishing nets, buoys (Browne, 2015). They also can be made from the fragmentation of larger objects that causes ever smaller pieces of plastic into the environment. MP amounts and classification of potential sources vary considerably among studies (Collignon et al., 2012). The MPs can be originated from overseas harbors, industrial production sites, human activities such as tourist and urban runoff, textile industries and sewage treatment plants (Dubaish and Liebezeit, 2013; Cesa et al., 2017). In addition, different types of particles made from different sources like road surface markings made of thermoplastic composite paints, fibers derived from synthetic textiles and fragments of large litter items such as plastic bottles and packaging materials (Horton et al., 2017). Even, the variety of MPs colors confirms the multiple sources of MPs (Yu et al., 2016).

The presence of colored MPs confirmed that they originate from synthetic and may be enriched with trace organic substances. Then, MPs are classified as primary (manufactured in small size) or secondary (derived from larger plastics) based on morphology. In the other term, they can be classified as primary or secondary based on shape and surface texture (i.e., smooth edges/texture, symmetrical shape classified as primary) (Estahbanadi and Fahrenfeld, 2016).

Primary MPs originate from spillage during plastic production or recycling and micro-cleansing particles in personal care products (Anderson et al., 2017). These products, such as facial scrubs, have been identified as potentially important primary sources of MPs to the environment especially marine (Conkle et al., 2018). As studied by Estahbanadi and Fahrenfeld (2016), the size distribution of MP in four personal care products were 63–125 μm, 125–250 μm, 250–500 μm, and 500–2000 μm (Browne, 2015).

Secondary MPs made from broken fragments of larger plastic pieces, including, marine litter, synthetic fibers from laundry discharge litter from landfills and industrial or agricultural sources. They are deriving from the fragmentation of larger plastic debris through mechanical forces, by thermo-degradation, photolysis, thermo-oxidation and biodegradation processes (Zhao et al., 2015). Therefore, identification of secondary MPs are difficult due to the large diversity of sources and pathways (Stolte et al., 2015). In addition, Due to their chemical composition and large surface-to-volume ratio, study on composition of MPs is necessary (Wagner et al., 2014).

For example, around 93% of MPs in cosmetics are PE and some made of PP, PE PET and nylon (Eriksen et al., 2013). It can be noted that some significant differences between adsorption by microbeads and adsorption by PE particles can be observed. Although, direction of these effects as microbeads from cosmetics tended to adsorb lower concentrations of persistent organic pollutants (POPs) then PE particles (Napper et al., 2015).

More work has been done to use MPs as physical abrasives in domestic products. For instance, even the vessels can be source of MPs that can be originated from paint flakes off the vessel as reported by Anderson et al. (2017) and vessel traffic as reported by Tamminga et al. (2018). In fact, the understanding about the sources and pathways of MPs is needed to prevent the pollution of our environment (Browne, 2015).

3. Detection techniques

To evaluate the MPs pollution, selection of suitable identification method is crucial. The reliable method should achieve consistency in sampling techniques and taking into account the importance of analyzing the shape and chemical composition of MPs (Alomar et al., 2016). As described quantification methods in literature are limited, there is an urgent need to harmonize procedures for sampling, extraction, identification, assessment and quality assurance (Vandermeersch et al., 2015; Qiu et al., 2016). As discussed by Wesch et al. (2016), the most recent developments of methods for the identification of microfibers such as adoption of spectroscopic techniques should be standardized to monitor MPs more effectively. The detection techniques of MPs are summarized as follows:

1) **Visual Identification:** This method is necessary for separation of MPs from other organic or inorganic material in the sample residues. A visual assessment can help to distinguish MPs originating from field samples to MPs originating from laboratory contamination (Mathalon and Hill, 2014). Large MPs can be detected by this method while smaller particles should be observed using dissection microscope (Doyle et al., 2011). As reported by Lee et al. (2013), particles smaller than 1 mm cannot be identified and counted without microscopic observation and subsequent spectroscopic confirmation. By the way, for detection of polymer types of particles < 500 μm, this method is not suggested due to low level of identification. It also stated that this method can be applied for small transparent particles with 20 μm (Mintenig et al., 2017).
2) **Density Separation with Subsequent C:H:N analysis**: In this method, the polymers separated by difference in their density precisely while for the extraction of high density polymers, this method is not applicable. By weighing a certain volume of the solution, the density of the particle can be obtained. Density separation is useful for marine sediments due to their high density as MPs tend to sink more easily than lighter plastics. This method can be followed by C:H:N Analysis to identify the origin of plastic particles (Claessens et al., 2013).
3) **Pyrolysis-GC/MS:** After above-mentioned methods, it can be used to identify polymer types. It can be obtained by comparing the pyrograms results and selected standard polymers which obtained from the pyrolysis. Hence, this method is not recommended for processing large sample quantities due to the analysis of one particle

per run (Nuelle et al., 2014).

4) **Raman Spectroscopy:** basically, Raman is suitable method for identification of the most common plastic types in the marine environment (Lenz et al., 2015). In this method, only very small plastic particles (sizes below 1 μm) can be measured. It works as the sample is irradiated with a monochromatic laser wavelengths usually range between 500 and 800 nm and the results is compared to a known polymer spectra library to identify the composition of the particle (Young and Elliott, 2016). Recently Schymanski et al. (2018) found the particles with sizes smaller than 20 μm can be detected using high resolution of μ-Raman spectroscopy by > 80% efficiency.
5) **IR Spectroscopy:** FT-IR micro-spectroscopy is a tool that combines FT-IR spectroscopy with microscopy buy using micro-FT-IR and infrared bands. It is reliable method for the identification of MPs polymer type with low cost and ease of use (Browne et al., 2010; Lusher et al., 2014). The detection of MPS is based on stimulation of molecular vibrations with infrared radiation depend on the composition and molecular structure of a substance and wave-length. Plastic polymers possess highly specific IR spectra with distinct band patterns for detection of composition and origin of MPs in marine (Van der Hal et al., 2017). Table 2 shows the comparison of detection methods of MPs based on their advantage and limitations.

Recently, Serranti et al. (2018) developed an innovative approach, based on HyperSpectral Imaging (HSI) in order to classify the polymer type, size definition and shape characteristics of marine MPs in one shot. HSI can be used for the chemical characterization of the marine MPs almost close with FT-IR results which is fast, reliable and reliable and non-destructive and no sample preparation is required. For Identification of MPs, combination of methods can be used which is described as follows:

3.1. Combined methods

Use of a combination of both the microscope and spectroscopic methods is recommended to analyze huge number of samples. For this purpose, first FTIR or Raman should be applied to create sample-based criteria for the identification of major and typical MPs in sample groups. Then the stereomicroscope can be used to count MPs according to screening results (Song et al., 2015a). Recently, Herrera et al. (2018) suggested that the combined method of density separation with 96% ethanol was a standard method for extracting MPs from beach samples. Also, to analyze MPs in freshwaters, the use of combined different techniques can improve data which is difficult for investigation by single method (Li et al., 2018).

For example, Löder and Gerdts (2015) used focal plane array (FPA)-based micro-FTIR spectroscopy as a promising technique to identify polymer origin of MPs particles. This method can detect particles < 500 μm which were not only detectable by visual inspection. This method also reduce the analysis time in compare to other methods as detection time is < 9 h compared to several days (Tagg et al., 2015).

A new extraction method of MPs is proposed based on hypochlorite digestion and isolation of MP from the membrane by sonication that adapted to a subsequent analysis by Raman spectroscopy. It reduce the fluorescence problems, resulted in better identification of anthropogenic particles from stomach contents of fish to improve the detection of MPs pollution in marine environment. Hence, more accurate determination of the type and number of ingested MP can be obtained using this method (Collard et al., 2015).

Another combined method is proposed by Claessens et al. (2013), for MPs extraction from sediment and invertebrate tissue. This method consisted of a volume reduction of sample by elutriation, followed by density separation using a high density NaI solution which has a considerably higher extraction efficiency for sediments. For MPs extraction from animal tissues, it works based on chemical digestion resulted in high efficiency (94–98%). As a conclusion, these new methods give us a

Table 2
Comparison of different MPs detection techniques.

Method	Procedure	Application/key point	limitation	Reference
Visual Identification	Using microscope too observe the composition	MPs source, degradation stage, type, color and shape of particles can be detected easily.	Size limitation of higher than 1 mm. Time-consuming with high rate of error > 20%.	(Hidalgo-Ruz et al., 2012)
Sieving	Materials retained in the sieve are collected (and sorted),	Distinguishing different size categories of MPs	Ancient method and not too accurate.	(McDermid and McMullen, 2004)
Density Separation with Subsequent C:H:N Analysis	Separation based on difference in density and velocity of the sample	Detection of polymer type but not a rigorous chemical analysis	Long time and high effort is needed. Not applicable for smaller particles.	(Morét-Ferguson et al., 2010)
Pyrolysis-GC/MS	Comparison of polymer origin with their characteristic combustion products	Relatively more accurate than density separation	Only small size particles can be manipulated manually that resulted in limitation of lower size particles analysis.	(Fries et al., 2013)
Raman Spectroscopy	Sample is irradiated with a laser wavelengths in the range of 500 to 800 nm	Facilitate the detection of even the smallest MPs. Accurate method to identify the abundance and polymer types of MPs.	Fluorescent samples excited by the laser cannot be measured.	(Song et al., 2015a), (Imhof et al., 2012).
IR Spectroscopy	Infrared radiation causes molecular vibrations	An optimal technique for the identification of MPs polymers with highly specific distinct band patterns	Due to high absorption rate, black particles are not detectable. The results of analyzing secondary MPs is unclear due to the size.	(Harrison et al., 2012) (Talvitie et al., 2017)

comprehensive understanding of the presence of MPs in the marine and biota. In following section, we reviewed the existence of micro-plastics in biota and different aquatic environments.

4. Micro-plastics pollution in aquatic environment

Due to the interactions with pollutants such as different types of heavy metals and hydrophobic pollutants, MPs pollution considered as a serious issue to aquatic environment and marine biota (Teuten et al., 2009; Ma et al., 2016; Vedolin et al., 2017; F. Wang et al., 2018). In this review, we categorized aquatic environment under three categories as marine includes beaches and ocean, fresh waters like rivers and lakes and WWTPs.

4.1. Marine (beaches and ocean)

MPs pollution has been reported in marine ecosystems such as sediments, open waters and organisms (do Sul and Costa, 2014; Auta et al., 2017). Studies on MPs in marine area have been carried out on both the east and west coasts of North America, South America, Antarctica, Asia, Oceania, Europe, southern Africa and Mediterranean and polar (Wessel et al., 2016; Waller et al., 2017; Obbard, 2018). The fate and impact of MPs in the marine environment are still has not been fully identified (Avio et al., 2017). As found by Clark et al. (2016), the spatial distribution and long-term fate of MPs in the marine environment still in unclear. It depends on such factors includes (1) their chemical structure (2) density to that of sea water (3) ease of weather ability (4) additives incorporated into their formulation (5) nature of polymers (6) ecological impacts and (7) Fragmentation ability (Andrady, 2017; Arias-Andres et al., 2018).

According to the literature, it is assumed that the majority of plastic in the oceans are MPs which include microfibers (Mathalon and Hill, 2014; Veerasingam et al., 2016). For instance, an average abundance of MPs in Atlantic Ocean and Mediterranean Sea is up to 1 MP per 25 cm^3 with recovered depth from 1176 to 4843 m (Van Cauwenberghe et al., 2013). La Daana et al. (2018) discovered that in sub-surface waters (8 to 4369 m) of Arctic central basin MPs exist which dominated by fibrous and the synthetic polymer polyester.

Beaches are a reservoir of highly fragmented plastic debris that transport MPs particles back to coastal waters and finally the open ocean (Fok et al., 2017). As reported by Herrera et al. (2017), there is a high level of marine debris pollution in the Canary Island coastal area which mainly depends on local-scale wind and wave conditions. The types of debris found were mainly plastic fragments and tar that originated from the open sea. Even, mesoscale ocean dynamics have impact on plastic debris distribution at the sea surface within subtropical gyres (Brach et al., 2018). Table 3 shows recent studies on MPs pollution in marine environment around the world.

4.2. Fresh waters (rivers and lakes)

The presence of MPs for inland lakes in remote areas has negative impact to the environment and became a global issue (Zhang et al., 2016). By the way, MPs are widely distributed in waters and sediments of fresh waters, their presence and effect on environment has been received more attention since few years ago (Eerkes-Medrano et al., 2015; Vaughan et al., 2017). They float in the surface water and stay in the water sink into sediments of the lake. While, the sediments are more stable than water their transportation rate in sediments are slower than those floating in surface water (Nel et al., 2018). Therefore, it can be concluded that there is a direct correlation between distance of contamination source and MPs pollution levels in sediments (Su et al., 2016).

As the significance of MPs contamination in freshwater systems has been observed recently even in drinking water, research about this issue is necessary (Li et al., 2018). Besides, high level of MPs pollution in marine environment is a potential threat to human and animal's life and some plan should be strategized to reduce the effect of MPs in urban areas such as fresh waters (Eriksen et al., 2013). Therefore, the role of the freshwater system as major source of MPs to the marine environment should not be neglected (Sighicelli et al., 2018). Research about river systems and watersheds can provide the knowledge to the people to understand the needs of solving MPs pollution in fresh waters (Miller et al., 2017). Based on collected data, many studies have been carried out to estimate and investigate the MPs pollution in fresh waters such as river and lakes around the world as shown in Table 4.

4.3. Wastewater treatment plants

WWTPs effluents are considered as a major source for MPs, as the municipal and industrial effluents are containing macro and microplastic. Large plastics are being removed in water treatment systems using different technologies but not specified to retain small MP (Mani et al., 2015). Although, there are not many published studies regarding the MPs pollution in WWTPs, but the significant attention is needed similar to that recommended for marine environment (Prata, 2018). As reported by Murphy et al. (2016), one of the main contributors of MPs pollution to the environment is municipal effluent discharged from wastewater treatment. They contain high level of personal care products which have plastic microbeads. For example, Installed post-filtration unit of Oldenburg can reduce the load of MP and synthetic fibers in high level (Mintenig et al., 2017). Meanwhile, the presence and abundance of micro-fibers differed between sampling sites that received effluent from a sewage treatment facility (Reynolds and Ryan, 2018).

Microbeads are designed to be disposed of via WWTPs facilities. Although, this system are not able to remove manufactured MPs. Based on the statistics, about 8 trillion microbeads are released into aquatic environments daily via WWTPs (Rochman et al., 2015). Currently, tertiary level of WWTPs also considered as a source of microlitter and MPs (Talvitie et al., 2017). In contrast, Carr et al. (2016) reported that the effluent discharges from both secondary and tertiary WWTPs had minimum contribution to the MPs loads in oceans and surface water environments. Table 5 shows the recent studies of MPs pollution in WWTPs.

5. Micro-plastic pollution in Biota

Many organisms (whales, shellfish, fish turtles) swallow pieces of plastic, which can accumulate in their digestive system of biota (Matsuguma et al., 2017). As documented, cetacean can swallow plastic during secondary ingestion accidentally, which occurs during feeding animal with prey which have ingested debris previously. It means that the degradation of macro-litter in micro-litter induces many other impacts on marine fauna too (Di-Méglio and Campana, 2017). Espinosa et al. (2018) found that continues exposure of fish to PVC or PE could destroy fish immune system due to the oxidative stress in the fish leucocytes. Hence, PVC showed more changes in fish leucocytes than PE. In another study, the highest number of ingested MPs *Macoma balthica* was found on the first sampling occasion, indicating that the plastic particles were not accumulating in clams during the experiment (Näkki et al., 2017).

Once MPs ingested by marine organisms, the serious physical and toxicological effects maybe occurred in their bodies. Therefore, the effects of MPs on the health of different aquatic species should be investigated. These effects are categorized as: a) physical (related to the shape, color and dimension of the particles) and b) chemical (related to the presence of additives and/or sorbed chemical contaminants) (Karami et al., 2017a; Rainieri et al., 2018). For instance, some parameters such as the level of contamination, location and local human activity are important in MPs accumulation in fish muscles (Akhbarizadeh et al., 2018).

MPs enter to the food chain through ingestion by marine organisms

Table 3
MPs pollution in marine (recent studies since 2013).

Location	Sample type	Sample collection	Detection method/ pretreatment type	MP range/average	MPs concentration	Type/size/color of MPs	Remarks	Reference
Six beaches near the Nakdong River Estuary, South Korea	Styrofoam was the most abundant item both in MPs and mesoplastic debris	Water	Sieving, microscopic observation followed by spectroscopic determination	–	27,606 particles/m^2 for large MPs	MPs consisted of intact plastics, fragment and Styrofoam.	The MPs abundance was strongly correlated with the abundance of mesoplastics,	(Lee et al., 2013)
Recreational beaches in Mumbai, India	Consumer and household related materials	Sediment	the plastic debris was air-dried and individual plastic particles sorted, weighed	Small particles (1–20 mm) were predominant with 41.85% microplastics (1–5 mm)	155.33 ± 63.48 m^{-2}	MPs accumulation varied in terms of weight (7.30–25.73%) and number (32.56–55.33%)	75% of plastics in beach sediment are within the size range of 1–20 mm	(Jayasiri et al., 2013)
Beaches in Slovenia	Plastic 64%, paper (19%), followed by glass and ceramics (11%), metal (2%), and rubber (1%)	Sediment	Combined decantation and inverse filtration	Median density was 1.25 items m^{-2} and weight of 4.45 g m^{-2}.	133 to 155.6 particles kg^{-1}	The majority of MPs (74%) was larger than 1 mm in blue, red and yellow color.	No relation between tourism activity and marine debris distribution at the sampling time.	(Laglbauer et al., 2014)
Norderney, North Sea coast of Germany,	Majority was PP, followed by PE, PET, PVC, PS and PA.	Sediment	Sieving, density separation, visual microscopic and gas chromatography/ mass spectrometry	Fibers ranged from 0.5 mm to a few cm in length, with a diameter of < 100 µm.	2.3 particles kg/dry sediment	Translucent colored fibers, (black, brown and beige)	The occurrence of small potential MPs did not correlate with the visible plastic debris.	(Dekiff et al., 2014)
Northeast Atlantic Ocean	Fibers, fragment, bead, foam while the majority was fibers by 95.9%	Water	Raman	94% of samples contained plastics with the size between 1.25 and 2.5 mm	2.46 particles m^{-3}	Blue, black, orange and red were dominant.	The majority collected samples were from a large distance from shore and urban areas.	(Lusher et al., 2014)
Halifax Harbor, Nova Scotia	Fibers was highest in sediments	Sediment	Floatation in saline solution and filtration	–	20 to 80 MPs/10 g sediment	Spherical microfibers in brightly colored form.	After five times extraction, the most of MPs were recovered.	(Mathalon and Hill, 2014)
German Baltic coast	Secondary MPs such as fibers and fragments	Sediment	Density separation, sieving, microscopic visualization and FTIR	MPs 43–132 fibers/ kg sediment	0–7 particles/kg sediment	The dominant colors were blue, violet, or green hues	MPs concentrations of 0–7 particles/kg and 2–11 fibers/kg dry sediment.	(Stolte et al., 2015)
Jinhae Bay, South Korea	Paint resin particles was 75% followed by spherules 14%, fibers 5.8%, PS 4.6%, and sheets 1.6%	Water	Microscope and FTIR, ATR	Particles number ranged from 33 to 83 particles/L.	88 ± 68 particles/L	Green, blue, and red	The floating MP abundance in surface water was the highest in worldwide.	(Song et al., 2015b)
South-eastern coastline of South Africa	Secondary MPs such as fibers and fragments	Sediment and water	Dissecting microscope	–	In sediment 688.9 ± 348.2 and 3308 ± 1449 and water 257.9 ± 53.36 and 1215 ± 276.7 particles/m^{-3}	Blue/black and red were the dominant colors	Synthetic fibers identified as a significant source of pollution.	(Nel and Froneman, 2015)
Pacific coast of southern Mexico	Fibrous MPs	Sediment	Density separation, followed by filtration and visual inspection	The average thickness was 4.247 to 50.2 µm, and the total length ranged 0.004266–4.491 µm	48 to 69 MPs/30 g sediment	Dominant colors were white > black > blue > red > light brown	The effect of tourism in accumulation of MPs along the shores was directly related to survival of marine organisms.	(Retama et al., 2016)
Kamilo and Kahuku Beach, Hawai'i	Most of the fragments were PE and some PP	Sediment	Sieving, microscope observation and Raman	The majority of MPs (95.9%)size was 2–4 mm.	–		Color frequency distribution was not significantly different between the two beaches.	(Young and Elliott, 2016)

(continued on next page)

Table 3 (*continued*)

Location	Sample type	Sample collection	Detection method/ pretreatment type	MP range/average	MPs concentration	Type/size/color of MPs	Remarks	Reference
						Dominant color was white/transparent followed by blue green black/gray red/pink yellow orange brown and purple.		
Northern Gulf of Mexico estuaries	PP and PE were most abundant	Sediment	combination of sieving density separation and visual sorting	MPs abundance ranged from 5 to 117 pieces per square/m	13.2 ± 2.96 and 50.6 ± 9.96 MPs per m^2	Shapes of strands, hard, film and foam in blue, green and majority white	PE and aliphatic polyamide had the lowest quantities.	(Wessel et al., 2016)
Northern coast of Taiwan	Majority were PE and PP	Sediment	Synchrotron-based FTIR spectroscopy	Majority were classified at size of 0.25 to 4 mm.	484 and 532 particles per 0.0125 m^3	Most of the fibers were white, gray and transparent.	Significant negative trend between the size of the particles and their numbers observed.	(Kunz et al., 2016)
Slovenian part of the Northern Adriatic	Over 80% of the particles were PE	Water	Sieving and stereomicroscope identification, image analysis by NIR	The total dry weight of the particles was 4,7 g of particles and smaller than 5 mm in size	406 × 10^3 particles/ km^2	The average abundance of MP from all samples was 472 × 103 ± 20-1 × 103 particles/ km^2 (6,29 ± 2,68 particles/m).	The area had significant locational and temporal variation in MP pollution.	(Gajšt et al., 2016)
Qatar	PP	Water	Microscope and FTIR	Sizes ranging from 125 µm to 1.82 mm and fibrous 150 µm to 15.98 mm.	0.71 particles m^{-3}	Majority were blue and opaque white were	MPs showed evidence of oxidation, based on the presence of carbonyl groups in FTIR analysis.	(Castillo et al., 2016)
Mediterranean Sea, Spain	Filaments were > 60% of MPs.	Sediment	Sieving, density separation and microscope observation	MPs were in two grain size fractions: 2 mm > x > 1 mm and 1 mm > x > 0.5 mm	100.78 ± 55.49 to 897.35 ± 103.31 MPs/kg of dry sediment.	MPs color were mostly black or blue	There was no clear trend between sediment grain size and MPs deposition in sediment.	(Alomar et al., 2016)
Goa coast, India	PE and PP were dominant polymers	Water	Stereoscope microscope and FTIR- Attenuated Total Reflectance (ATR) spectroscopy	–	–	Dominant color of MPs was white followed by yellow.	MPs characteristics proved that they could be originated from ocean-based sources.	(Veerasingam et al., 2016)
Bohai Sea, China	PEVA (polyethylene vinyl acetate), LDPE (light density PE and PS)	Sediment (sand)	Density separation, microscope and FTIR	–	102.9–163.3 pieces/ kg sand	Purple, black, green, pink and brown were dominant colors	Surface samples contained higher MPs concentrations than deep samples.	(Yu et al., 2016)
Scapa Flow, Orkney, Scotland	45% were poly (tetrafluoro) ethylene, 15% PE or 10% PA, 8% PS and 3% polyacrylonitrile	Sediment	density separation, Super-saturated NaCl flotation and FTIR	–	Mean were 730 and 2300 kg^{-1} sediment (DW)	Dominant colors were blue > black > purple = white > red > brown > green	There was no statistically significant difference between average particle and fiber concentrations.	(Blumenröder et al., 2017)
Beaches of Kaliningrad region, Russia	Fragments of synthetic fibers and plastic films; foamed plastic PS and plastic fragments	Sediment	Optical microscope	MPs ranged from 370 ± 1290 to 7330 ± 18,800 mg per m^2	1.3 and 36.3 items per kg dry sediment	Purple, red and yellow were dominant colors	MPs ranged from 370 ± 1290 to 7330 ± 18,800 mg per m^2.	(Esiukova, 2017)

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Table 3 (*continued*)

Location	Sample type	Sample collection	Detection method/ pretreatment type	MP range/average	MPs concentration	Type/size/color of MPs	Remarks	Reference
Coasts of Tyrrhenian Sea, Italy	Filaments > 88% and fragments < 9% in each sample	Sediment	Sieving and stereo microscope	MPs size between 5 and 10 mm with the minimum between 0.5 and 1.0 mm.	From 42 to 1069 items/kg	Dominant colors were black, blue and clear	There was no Statistically differences in levels of plastic concentrations of samples of different origin.	(Cannas et al., 2017)
Baltiysk Strait, Russia	Fibers were higher rather than fragments and films	Sediment	Density separation, wet peroxide oxidation and stereomicroscope	Size ranged from 0.15 to 0.43 mm	34 ± 10 MPs/kg DW	–	MPs average concentration of 34 ± 10 items/kg DW.	(Zobkov and Esiukova, 2017)
Terra Nova Bay (Ross Sea, Antarctica)	Fibers were the most by 42.8%, followed by film 35%, and fragments 22.2%	Sediment	Microscope and FTIR, ATR	Plastic particles in the samples ranged from 0.3 to 22 mm in length	1 to 90 items/m^2	Yellow, white and black were dominant colors	Highest MPs number and weight was 676.5 ± 536.4 debris m^{-2} and 3.03 ± 2.85 g m^{-2}, respectively.	(Munari et al., 2017)
Strait of Hormuz, Persian Gulf	Majority were fibers	Sediment	Fluidization/ floatation and FTIR analysis	Width ranged from 0.02 to 4.69 mm and length from 0.14 to 50.00 mm	2 to 1258 par/kg in different beaches	Dominant colors were transparent, yellow, blue and black	The most recovered polymers were PE and PET.	(Naji et al., 2017b)
Israeli Mediterranean coastal waters	Fragments were dominant by 93.6–97.7%	Water	Microscopic observation	MPs size 0.3–5 mm	7.68 ± 2.38 particles/m^3	Light-colored (white or transparent) were dominant colors	No significant differences between the variety and abundance of the six colors was observed.	(Van der Hal et al., 2017)
Northeast Levantine coast of Turkey	Fragments were dominant by 60%	Sediment	Density separation, followed by filtration and microscopic	Size range of plastic particles was determined to be 300 μm–3 cm, with an average size of 2,9 mm	0.376 item/m^2	Out of 15 colors, most dominant color was trans- Parent. The shape was in order of Irregular > flat > -elongated > spherical > cylindrical.	There was no statistically significant relationship between the number of species and plastic debris amount.	(Gündoğdu and Çevik, 2017)
Coastline of Qatar Gulf	Low density PE and PP	Sediment	Sieving, density separation and filtration	Size range 1 and 5 mm	36 and 228 particles m^{-2}	Blue was dominant by 75% followed by black 9.9%, red 6.3%, green 4.4%, gray 2.2%	There was a heterogeneous distribution of types, colors and sizes of MPs.	(Abayomi et al., 2017)
Levantine coast of Turkey	PE, PET and PP were dominant.	Water	ATR-FTIR analysis	On average 86,3 kg/km^2 in weight of plastic.	2.6 item/m^2	–	Plastic types (PE, PET, PP) demonstrate significant differences with regard to species diversity and abundance.	(Gündoğdu et al., 2017)
Coast of Guangdong, South China	PS foams and fragments	Sediment	Sieving and ATR FTIR	Nearly 98% of the debris consisted of MPs by 0.315–5 mm	0.1589–5.5884 Plastic debris weight (g/m^2)	–	The mean and median abundances of MPs were high at 6675 ± 7021 (± SD) and 3146 ± 4181 (± MAD) items/m^2, respectively	(Fok et al., 2017)
Persian Gulf, Iran	PE, nylon, and PET	Sediment	Density separation, flotation and FTIR	56% MPs were in the size category of 1–4.7 mm length.	61 ± 49 particles/ kg/dry sediment.	Transparent, white, green and red were dominant colors.	Persian Gulf was not categorized as a hot spot for MP pollution.	(Naji et al., 2017a)
Bohai Sea, China	PE, PP and PS	Water	Microscope and FTIR	55% of MPs was ranged at 0.3–5 mm	0.33 ± 0.34 particles/m^3.	Dominant colors were white, transparent, green and yellow respectively.	Fishing lines and floating foams were dominant.	(Zhang et al., 2017)

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Table 3 (*continued*)

Location	Sample type	Sample collection	Detection method/ pretreatment type	MP range/average	MPs concentration	Type/size/color of MPs	Remarks	Reference
North Atlantic Ocean, Scotland	PET, microfibers	Water	SEM and FTIR	Sizes ranged from a 0.4 mm for (PET) to a maximum of 8.3 mm for microfiber.	70.8 particles m^{-3}	Red by 42% was dominant color followed by black, green, orange, transparent	There was a hypothesis that MPs are exist in the global deep-sea.	(Courtene-Jones et al., 2017)
Different beaches across Europe	Fibers	Sediment	Density separation, and stereo-microscope	The majority of MPs size was < 1 mm	72 ± 24 to 1512 ± 187 kg/dry sediment	Dominant colors were blue and black	Western coasts of Mediterranean zone were less prone to MP accumulations.	(Lots et al., 2017)
Northern Gulf of Mexico	PE	Water	Microscope and FTIR	86.03% had size between 0.001 and 0.01 mm^2	4.8 to 18.4 particles m^{-3}	Mostly fiber and fragments.	This study reported the highest MPs pollution in inner continental shelf worldwide.	(Di Mauro et al., 2017)
Ross Sea (Antarctica)	PE and PP	Water	FTIR	–	0.0032 to 1.18 particles per m^3	Mostly fiber and fragments.	MPs concentration based on particle per m3 were lower than other oceans worldwide.	(Cincinelli et al., 2017)
Beaches in eastern waters of Hong Kong	PE, PP and PET were > 70%	Sediment	Sieving, microscope and FTIR	–	0.58 to 2116 items kg^{-1}/dry sediment	Fiber and fragment were the by 57.2% and 37.6%, respectively.	MPs abundance in mudflat was higher than sandy shore sediments.	(Lo et al., 2018)

(Cressey, 2016; Abidli et al., 2017). This situation threatens predators and humans' health who consume animals from polluted ecosystems (Guilhermino et al., 2018). As reported by Wright et al. (2013), there are various consequences from ingestion of plastics and MPs for various marine species such as turtles, fish larvae and mammals. In addition, some coefficients such as POPs exist in the MPs structure also can be ingested by marine biota (Steer et al., 2017).

The toxicity of leached chemicals from pellets to animal bodies depends on the exposure pathway and on the environmental compartment in which pellets accumulate (Nobre et al., 2015; Wen et al., 2018). It is generally hypothesized that biota in coastal regions have experienced a greater impact from MPs ingestion (Steer et al., 2017). The variability in ingestion rates could be due to differences in preferred habitat and the effects of wind, ocean currents transporting plastic debris and feeding behavior (Foekema et al., 2013; Murphy et al., 2017). Occupying the similar size fraction to sediments and some planktonic organisms, MPs have been ingested by marine biota via direct and indirect ingestion (Gall and Thompson, 2015). MPs were correlated to the ingestion of fish eggs, earthworms, and mollusks during their normal feeding and associated with the ingestion of other debris items (e.g. sand and wood) and (Peters and Bratton, 2016).

Research on the mussels demonstrated that the MPs were translocated from the gut to the circulatory system (Browne et al., 2008). Gut conditions such as temperature and pH are significant factors to enhance desorption rates and increase potential bioavailability to marine organisms. Therefore, desorption rates can increases at lower pH and higher temperature (Bakir et al., 2014). As found by Hall et al. (2015) ingested MPs wrapped in mesenterial tissue of *scleractinian* corals is retain within their gut cavity for at least 24 h which can impair their health.

As suggested by Claessens et al. (2013), there is a lack of suitable techniques to extract plastic particles from (soft) organic tissue which proved the on-going interest in the presence of MPs in marine organisms. Miller et al. (2017) stated that the most common techniques to for MPs detection in marine samples are visual examination, density flotation and acid digestion. For instance, in studies related to mussels usually acid digestion is used which is very destructive method with complete digestion of tissues (Vandermeersch et al., 2015). As reported by Lusher et al. (2017), extraction methods for ingested MPs by biota are dissection, depuration, digestion and density separation. Hence, in order to accuracy in data and analysis, these methods should be standardized. Although, techniques for extraction of plastics from organism still needs improvement in order to obtain higher accuracy of the results.

Therefore, there is a need to develop methods to evaluate the plastic exposure in free-ranging marine wildlife particularly exposed to MPs ingestion (Savoca et al., 2018). The digestive method for MPs particles protocol for MPs detection is: (1) no cellular or organic structures are visible; (2) if the particle is a fiber, it should be equally thick, not taper towards the ends and have a three-dimensional bending; (3) homogeneously colored/clear particles (Norén, 2007).

Some researchers developed new protocols and method for analysis of ingested MPs by Biota. For instance, Karlsson et al. (2017) developed enzymatic digestion protocol using proteinase K with a 97% recovery of spiked plastic particles and no degradation effects on the plastics in subsequent Raman analysis was observed. In another study by Cole et al. (2014), two enzymes *Proteinase K* and *cellulase* was used for biotic material removal, while retaining anthropogenic and inorganic material. They found that the optimized enzymatic protocol digested > 97% of the material present in plankton-rich seawater samples with no destroying in MPs debris.

Lo and Chan (2018) found slower growth rate during their larval stage of *Juvenile C. onyx* once receiving continuous MPs for 65 days. As stated by Santos et al. (2015), debris ingestion by *juvenile* marine turtles may cause of death due to blockage of gastrointestinal tract by debris. In addition, MPs concentration was 47.5 items per turtle which

Table 4
MPs pollution in fresh waters (recent studies since 2013).

Location	Sample type	Detection method	MP range/average	MPs concentration	Type/size/color of MPs	Remarks	Reference
Laurentian Great Lakes	Microbeads from consumer products	SEM/EDS	Size classes particles 0.355–0.999 mm consisted of 81% of total	0.043 particles/m^3	Color variation among particles < 1 mm but majority were blue, white and gold color.	20% of particles were < 1 mm.	(Eriksen et al., 2013)
Tamar Estuary, Southwest England	82% of the debris and fragments includes PE by 40%, PE by 25% and PP by 19%.	Sieving and FTIR	The 1–3 mm size category was the most abundant size.	0.028 particles/m^3	Colors were black and yellow. PP was present only in 1–3 and 3–5 mm and nylon only in < 1 and 1–3 mm	Significant difference in size frequency distribution between the spring and neap tides was observed.	(Sadri and Thompson, 2014)
Lake Hovsgol, Mongolia	Fragments and films were the most abundant MPS	Sieving and light microscope	Wide range of size from 0.333 to 5.00 mm	0.20 particles m^3	Majority were blue and white.	There was decreasing trend for MPs density with distance from the southwestern shore.	(Free et al., 2014)
Yangtze Estuary System, China	Microfibers	Floatation and stereomicroscope method	MPs had maximum size of 12.46 mm, and MPs (0.5–5 mm) constituted > 90% by number.	4137.3 ± 2461.5 and 0.167 ± 0.138 n/m^3	Transparent and colored MPs were the majority of MPs with small fractions of white and black.	The unique design of spatial scales provided good insights into MP source and fate.	(Zhao et al., 2014)
Pearl River Estuary, Hong Kong	Expanded PS	Sieve and Visual sorting	The highest abundance size was 258,408 items/m^2	Median number was 520 ± 688 highest 2098 ± 1705 and lowest 94 ± 44 items/m^2.	–	The amounts of large plastic and MP debris of the same types were positively correlated.	(Fok and Cheung, 2015)
Urban estuaries, China	PP and PE	Agitation, filtration and micro-Raman spectroscopy	Majority size was ranged 0.05 to 1.0 mm	Ranged from 10.6% to 119.8%	Colored MPs were the Majority followed by transparent, black and white	The concentrations of suspended MPs proved their bioavailability to low trophic organisms.	(Zhao et al., 2015)
Tibet plateau lake, China	PP, PE, PS and polyvinyl chloride	Sieving, Raman and SEM	The size of 1–5 mm was the most abundance	8 ± 14 to 563 ± 1219 items/m^2.	White, transparent, yellow and blue	MPs pollution can be problem in inland waters in remote areas which have lack of waste management strategy.	(Zhang et al., 2016)
Taihu Lake, China	Cellophane, followed by PE, PS and PP	μ-FT-IR and SEM/EDS	MPs were dominated by fibers 48–84% in size of 100–1000 μm	3.4–25.8 items/L in surface water and 11.0–234.6 items/kg sediment	White and transparent items were more common ranging from 29% to 44%	This study proved Taihu Lake was the most MPs polluted freshwater lakes worldwide.	(Su et al., 2016)
Lagoon-Channel of Bizerte (Northern Tunisia)	Fibers and fragments, without plastic pellets	Sediment sample	The average MP size for fibers was 1.39 ± 0.27 mm and for fragments 0.51 ± 0.19 mm	3000–18,000 items/kg dry Sediment	Colors were clear, green white, black blue and red.	Due to high level of MPs pollution, this site considered as a hotspot.	(Abidli et al., 2017)
Hudson River, USA	Microfibers as 43% cotton, 22% PET, 22% fluoro-polymer/Teflon 7% PP and 7% nitrocellulose/clay	FTIR	The size range of fibers were 1.24 ± 0.14 mm with a length of 0.33 to 3.59 mm	0.625 to 2.45 fibers L^{-1}	Dominant fiber and color was blue followed by black, transparent and red	No significant increase or decrease in the abundance of microfibers from river source to sea was observed.	(Miller et al., 2017)
River Thames, UK	Secondary MPs which had 91% fragments	Sieving, visual inspection and Raman	Majority had size from 1 to 4 mm	33.2 ± 16.1 particles/100 g sediment	Dominant colors were red and yellow.	At all sites MPs were observed which originated from different sources.	(Horton et al., 2017)
Urban surface waters of Wuhan, China	PE and PP were the dominant polymer	Stereoscopic micro-scope, SEM and FTIR	> 80% of MPs had a size of > 2 mm	1660.0 ± 639.1 to 8925 ± 1591 n/m^3	Colored particles were the major type, accounting for 50.4% to 86.9%, transparentpart24.7%	Residents and industries along the river shores can result in an increase in densities of MP particles.	(W. Wang et al., 2017)
Beijiang River	Pp and PE	Flotation, SEM, FTIR	–	178 ± 69 to 544 ± 107 items/kg sediment	Dominant colors were brown and blue	Majority of heavy metals carried by MPs were derived from inherent load.	(J. Wang et al., 2017)
Vembanad Lake, Kerala, India	Low density PE was the dominant polymer type	Sieving, wet peroxide oxidation and Raman	MPs in sediment was 96–496 particles m^{-2}	Mean abundance of 252.80 ± 25.76 particles m^{-2}.	Transparent and white were the dominant colors.	Film and foam were the dominant types of MPs.	(Sruthy and Ramasamy, 2017)

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Table 4 (*continued*)

Location	Sample type	Detection method	MP range/average	MPs concentration	Type/size/color of MPs	Remarks	Reference
Japan, Thailand, Malaysia, and South Africa	PE, PP, PS, PET, PVC, acrylics and polyamides	Density separation and FTIR	MPs ranged between 315 µm and 5 mm, while majority ranged 315 μm^{-1} mm	From 100 to 1900 pieces/kg-dry sediment.	White 57%, followed by brown 17% and black 14%, were the dominant colors	MPs abundance in sediment increased from the deeper to surface layers.	(Matsuguma et al., 2017)
Three Gorges Reservoir, China	PS was the most common type by 38.5% followed PP by 29.4% and PE by 21%.	Raman and FTIR	MPs < 1 mm accounted for 79.8% of total	In surface water ranged from 1597 to 12,611 n/m^3 and in the sediments form 25 to 300 n/kg wet weight	The dominant color was transparent, and small-sized particles were predominant.	No significant correlation between MPs concentrations in each sampling site was observed.	(Di and Wang, 2018)
South Carolina Estuaries	Fragments were dominants by 76.2% in Charleston Harbor and 77.5% in Winyah Bay	Sieving, H_2O_2 treatment, SEM and FTIR	MPs size in both Charleston Harbor and Winyah Bay was > 63 µm	In sediments of Charleston Harbor (413.8 ± 76.7) and Winyah Bay, (221.0 ± 25.6) $particles/m^2$.	Dominant colors were black, blue, colorless (translucent), gray, green, red, and white	Big variation in MPs concentration was due to the differences in currents, winds, and point sources.	(Gray et al., 2018)
Wind Farm, Yellow Sea, China	Fiber was dominant by 75.3% in water and 68.7% in sediment	Sieving, density separation and µ-FTIR	Size ranged from 0.05 mm to 5 mm	0.330 ± 0.278 $items/m^3$ in the surface water and 2.58 ± 1.14 items/g (dry) in the sediment	Colored, black and transparent-colored	MPs distribution in the local region affected by hydrodynamic effect based on human activities.	(T. Wang et al., 2018)
Italian Subalpine Lakes	PE 45%, PS 18% and PP 15%	Water	–	4000 to 57,000 $particles/km^2$	–	Fragments were dominant by 73.7%.	(Sighicelli et al., 2018)
Shanghai, China	PP was the most polymer	Density separation, microscope and µ-FT-IR	62.15% particles were between 100 and 500 µm	80.2 ± 59.4 items 100 g^{-1} dry weight	Blue, transparent, white and red	Spheres shape consisted of fiber and fragments were dominant.	(Peng et al., 2018)

accumulated in gastrointestinal system of green turtles (*Chelonia mydas*). In study by Van Cauwenberghe et al. (2015b) at six locations along the French–Belgian–Dutch coastline with a plastic body of 1.2 ± 2.8 particles g^{-1}, lugworms had a plastic retention efficiency ranging from 0.59% to 1.78% over a 2–6 year lifespan. As conclusion, marine invertebrates such as *Mytilus edulis* and *Arenicola marina* had on average 0.2 ± 0.3 and 1.2 ± 2.8 particles per gram of tissue, respectively. Table 6 shows the ingested MPs by different types of biota throughout the world.

6. Future prospects

For future studies, several aspects should be considered. As the most researchers studied the level of pollution, source and fate of MPs, the solution for these issue is still unclear. Hence, MPs recovery is almost impossible from natural water streams, identification of upstream sources to reduce pollution mitigation is recommended. In this content, policy makers has important role to regulate some roles for the industries to reduce MPs pollution which is threaten the human health as well as biota (Sharma and Chatterjee, 2017; Eriksen et al., 2018; Anbumani and Kakkar, 2018). If the toxic effects of MPs in biota can be evaluated comprehensively, the possibility of same effect to human health can be reduced (Rainieri et al., 2018). In addition, the estimation of polymer products fate and their released materials is necessary to evaluate their effect on environment in the short and long term (Hahladakis et al., 2018).

As plastic production is in direct relation with MPs generation, the possible solution for reduction of MPs impact in beaches are to scale down the plastic materials usage as well as applying smart recycling methods (Retama et al., 2016). Lusher et al. (2017) recommend further assessment of MPs impacts to predict the extent of the effects on ecosystems, ecological processes and biodiversity. For this issue, to determine the type of harmful MPs, the comparison of uptake and retention of the different categories and shapes of MPs is vital. For example, the behavior of films and fibers in marine environment is still unknown, comprehensive laboratory experiments to determine quantitative characteristics of different shapes of MPs in sedimentation process is required (Zobkov and Esiukova, 2017). Although, the role of MP films and fibers in marine environment is still unknown, it is required to continue laboratory experiments to determine quantitative characteristics for sedimentation and suspension processes of different shapes of MPs. As reported by Peng et al. (2018), future research should directed to the impact of exposure experiments on high-dose and short-term exposure as there are many related to field investigation of MPs pollution.

The investigations should be carried out to understand the real impact of these emerging micro-contaminants fundamentally that are present in aqueous environment and biota (Barboza and Gimenez, 2015). For instance, the differences between field and exposure experiments showed that using MPs in laboratory are different from the real conditions in term of relationship between exposure of MPs in mussels and water (Qu et al., 2018). As reported by Van der Hal et al. (2017), the ratio between MPs abundances and their abundances in biota in the same size is expected to be high and may induce even higher ingestion by marine biota.

For better understanding about environmental fate and ecological impacts of MPs future studies should focus on the development of new modelling approaches to assess transport of MPs in soil, sediments, and water (Lambert and Wagner, 2018). Maybe suitable solution can be detection and elimination of MPs sources and pathways to control inventories of materials or using novel equipment and technologies (Browne, 2015). Mai et al. (2018) suggested that for sediment sampling, location and depth should be specified and standardized while a certain food web of samples should be collected for sampling of biota.

In addition, future investigations can rely on sufficient validation of the MPs analysis, to improve the determination of MPs. Hence there are

Table 5
MPs pollution in WWTPs (recent studies since 2016).

Location	Sample type	MP range/average	Type/size/color of MPs	MPs concentration	Efficiency	Remarks	Reference
Los Angeles (USA)	Primary, secondary and tertiary	MPs were between 90 and 300 μm in width and 100–600 μm in length	More than 90% of these MPs were irregularly shaped blue polyethylene fragments.	Around 90 particle/L	95–99%	The majority of MPs was similar to the blue PE particles present in toothpaste.	(Carr et al., 2016)
Raritan River (USA)	Primary and secondary	In downstream of WWTP, The concentration of MPs was 125–250 with 250–500 μm size.	Upstream (white) and downstream (gray). Secondary MPs was the dominant in size (66–88%)	27.8 to 43.9 particle/m^3	–	A moderate correlation between MPs and distance downstream was observed.	(Estahbanadi and Fahrenfeld, 2016)
US	Tertiary		Fibers were the most common type of particle 59% followed by fragments 33%. Mostly black and gray.	0.004 to 0.195 particle/L	–	Average 4.4×10^6 particles were released per facility per day	(Mason et al., 2016)
Scotland	Secondary	Flakes 67.3%, fibers 18.5%, film 9.9%, beads 3.0%, and foam 1.3%	PA, PE and PP were the most dominant types.	0.25 to 15.70 particle/L	98%	Significant difference in the amount of MPS between the four sampling sites was found.	(Murphy et al., 2016)
Netherlands		Particle sizes between 10 and 5000 μm	Sewage sludges at three of the WWTPs had high number MPs of 650 particles kg^{-1} wet weight	9 to 91 particles L^{-1}	72%	All the influents and effluents of all WWTPs had MPs and MPs entering to the surface water systems.	(Leslie et al., 2017)
Australia	Primary, secondary and tertiary	Size range of 25–500 μm	PE was highest in secondary and primary and PET in tertiary	0.28 particles/L	92–99%	Synthetic fibers from clothing needs more attention rather than microbeads form personal care.	(Ziajahromi et al., 2017)
Oldenburg-East-Frisian, Germany	Primary, secondary and tertiary	MPs ranging from 0 to $5 \times 10^1\ m^{-3}$ MP > 500 μm and 1×10^1 to $9 \times 10^3\ m^{-3}$ MP < 500 μm.	Black/blue, red, transparent were dominant.	1 to 10 particles/L	97%	There was no correlations between MP numbers, sizes or polymers and population.	(Mintenig et al., 2017)
Ljubljana, Slovenia	PE microbeads	Size of 37 to 95 μm	Average concentration in body and facial scrubs was 4.82 g/100 mL and 0.74 g/100 mL, respectively.	21 particles/m^3	87%	Even the low concentrations of MPs was concern for the environment due to their persistency.	(Kalčíková et al., 2017)
Viikinmäki, Helsinki Region, Finland	Primary and secondary	Size ranged from 100 to < 300 μm	Pre-treatment had the greatest effect on size distribution	380 to 686.7 particles/L^{-1}	99%	MPs consisted of PE fragment which usually found in some widely used cleansing scrubs.	(Talvitie et al., 2017)
Mikkeli, Finland	Primary and secondary	64% of MPs were smaller than 1 mm	Fibers accounted for 96.3% of total MPs while PE was the most abundant polymer by 63.9%.	0.1 and 1 0.1 to 124.7 MPs/L	98%	Due to high variation in MPs, several sampling should be conducted.	(Lares et al., 2018)

Table 6
MPs pollution in biota (recent studies since 2013).

Location	Microorganism	Accumulation part	Detection method	MP range/type	MPs concentration	Type/size/color of MPs	Remarks	Reference
Ionian Sea (Eastern Mediterranean)	Deep water fish such as *P. violacea*, *G. melastomus*, *S. blainville*, *E. spinax* and *P. bogaraveo*	Gut	Stereomicroscope,	Fragments was the highest by 56.0%, followed by plastic bag fragments 22.0%, fragments of fishing gears 19.0% and textile fibers 3.0%	1.3 pieces of litter per fish	Dominant colors were blue, brown, black, transparent and green. Their size ranged from 5 to 60 mm.	The number of debris items per fish ranged between 1 and 6 (1.3 ± 0.2 of ingested pieces).	(Anastasopoulou et al., 2013)
English Channel	Pelagic and demersal fish	Gastrointestinal tracts	FT-IR Spectroscopy	The size ranged from 0.13 to 14.3 mm with the most common size of 1.0–2.0 mm.	1.90 ± 0.10 number of pieces per fish	MPs were fibers 68.3% fragments by 16.1% and beads 11.5%. Black was the most color by 45.4%.	PE by 35.6% and the semi-synthetic cellulosic material, rayon by 57.8% were most common types.	(Lusher et al., 2013)
Mussel farm in Germany	Two bivalves species: *Mytilus edulis* and *Crassostrea gigas*	Gut	Micro-Raman spectrometer	In *M. edulis* ranging from 5 to 10 µm (50.0%), while in *C. gigas*, 11–15 µm (29.6%) and 16–20 µm (33.3%).	In mussels 0.36 ± 0.07 and oyster 0.47 ± 0.16 particles per gram tissue (ww).	Dominant colors were red and blue.	The annual dietary for European shellfish consumers can be 11,000 MPs per year.	(Van Cauwenberghe and Janssen, 2014)
Halifax Harbor, Nova Scotia	wild and farmed blue mussels (*Mytilus edulis*),	Digestive tract	Hydrogen peroxide treatment	The average number in wild mussels was ~170/5 mussels while in farmed mussels was ~375/5 mussels.	170 and 375 per wild and farmed mussel	Colorful, transparent and black	Significantly more MPs counted in farmed mussels compared to wild mussels.	(Mathalon and Hill, 2014)
Santos Bay The State of São Paulo, Brazil	*Lytechinus variegatus*	Stomach	Elutriate and pellet–water interface assay	Larvae development varied from 17.2% to 53.3%, with a mean of 34.6%.	–	Raw and beach-stranded plastic pellets increased anomalous embryonic development by 58.1% and 66.5%, respectively.	Plastic pellets act as a vector of pollutants, especially for plastic additives found on virgin particles.	(Nobre et al., 2015)
Northern Ireland	Adult whales	Digestive tract	Microscope and FTIR	Mean length of 2.16 mm (± 1.39, range 0.3–7 mm)	2.95 MPs per fish	29 particles (58% fibers; 42% fragments) with a mean of 7.25 particles per compartment (± 2.63, range 5–11).	Marine mammals are exposed to MPs via trophic transfer from prey species	(Lusher et al., 2015)
China	Bivalves	Soft tissue	H_2O_2 treatment, Floatation and filtration, microscope observation, FTIR	Majority of MPs were fragments, fibers and pellets.	4.3 to 57.2 items/individual for bivalves	The main colors were black, blue, white, red, white and transparent.	250 mm was the most common size by 33% to 84% of the total MPs.	(Li et al., 2015)
Adriatic Sea, Italy	Adriatic fish mullet	Gastrointestinal tracts	Combination of density gradient separation and oxidant treatment, FTIR	Fragments 57%, followed by lines 23%, films 11% and pellets 9%	1 to 1.78 items/individual per fish	Size of 43% particles was 1–0.5 mm in sampled fish. The most common polymer was PE 65% followed by PET 19%.	Density gradient separation and oxidation treatment had a 90% yield.	(Avio et al., 2015)
Mediterranean Sea	Large pelagic fish (*Xiphias gladius*, *Thunnus thynnus* and *Thunnus alalunga*)	Stomach	Stereomicroscope coupled with Axiovision digital image	Mesoplastics were more abundant in swordfish stomachs by 44.4%, whereas albacore ingested more MPs about 75.0%.	4 to 16 number of plastic debris per fish	In different shapes and color; transparent and white were in all top predators, while blue and yellowish were in bluefin tuna and swordfish.	Positive correlation between the level of bioaccumulative and toxic compounds and alteration on the reproductive system.	(Romeo et al., 2015)
Spanish Atlantic and Mediterranean coasts	Demersal fish	Stomach	Visual identification, alkaline digestion and stereoscopic microscope	Average of 1.56 ± 0.5 items per fish, and the size of MPs ranged from 0.38 to 3.1 mm.	1.56 ± 0.5 items per fish	The dominant colors were black 51%, red 13%, gray 12.7%, blue 8.7% and brown 6.3%.	The highest abundance of MPs was 33.3% in red mullets followed by dogfish by 20.8%.	(Bellas et al., 2016)
North and Baltic Sea	Pelagic and demersal fish	Gut	Visual observation, FTIR and ATR	Almost 40% of the particles were PE.	0.03 ± 0.18 plastic items			(Rummel et al., 2016)

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Table 6 (*continued*)

Location	Microorganism	Accumulation part	Detection method	MP range/type	MPs concentration	Type/size/color of MPs	Remarks	Reference
						Dominant colors were blue and black in the size range of 150 μm up to 3 mm length and 5–30 μm in diameter.	No direct effects of ingested MPs on the condition of fish could be determined.	
Brazos River Basin, Central Texas, USA	Sunfish bluegill (*Lepomis macrochirus*) and longear (*Lepomis megalotis*)	Stomach	Stereomicroscope	A significant difference for mean number of MPs per fish between the upstream and urban areas observed.	10.1–13.9 of plastic per fish	Dominant colors were gray and blue by 79.1% of the total sample.	Sunfish ingested MPs during their normal feeding habits.	Peters and Bratton (2016)
Swedish West Coast	Marine invertebrates and fish	Stomach	Digestion and extraction, light microscope and FTIR	Most common MPs were fibers.	1 and 3 particles per fish	Dominant colors were black 32%, blue 28%, red 9%, transparent 6%, and green < 1%	68% of analyzed individuals of brown trout had MPs.	(Karlsson et al., 2017)
Dutch river delta and Amsterdam canals	Common shore crab (*Carcinus maenas*); sand hopper (*Gammarus spp.*); periwinkle (*Littorina littorea*); blue mussel (*Mytilus edulis*) and Pacific oyster (*Crassostrea gigas*).	Digestive gland	FTIR	In body residues between 10 and 100 particles g^{-1} dw were measured.	11 to 105 particles g^{-1} dw	Colorless and black were the most colors and fibers were the most one.	Suspended MPs in the water phase have the potential to be transported to the sea.	(Leslie et al., 2017)
Northeast Atlantic around Scotland	Demersal & pelagic fish	Gastrointestinal tracts	Dissection microscope and FTIR	Plastics ranged in size between 0.1 and 15 mm.	1.8 (± 1.7) number per fish	Dominants colors were black 43.0% followed by clear 21.9%, blue 13.2%, red 11.4%, green 9.6% and white 0.9%.	Ingestion was much higher in species found in shallower coastal waters than species in deeper further offshore waters.	(Murphy et al., 2017)
Pacific and Grays Harbor counties, Washington	Northern Fulmars (*Fulmarus glacialis*) and Sooty Shearwaters (*Ardenna grisea*)	Gastrointestinal tracts	Zoom binocular	Maximum dimension of a piece of hard plastic averaged 17 mm for Northern Fulmars and 22 mm for Sooty Shearwaters.	13.3 and 19.5 for fulmar and shearwaters respectively.	31% of fulmar intestines contained plastic with mean dimension 4.8 ± 0.3 mm and mass was 7.0 ± 1.4 mg while in Sooty Shearwaters, the incidence of plastic at 64% (16/25) was significantly lower than in fulmars	The average mass in *proventriculus* was 65.6 ± 14.9 mg/piece, and in *ventriculus* 25.3 ± 4.0 mg/piece.	(Terepocki et al., 2017)
Texas Gulf Coast, USA	Six marine fish species	Stomach	Stereomicroscope	Fragments were the most MPs.	0.45 to 1.38 of plastic per fish	The majority of MPs fibers were categorized as hue purple/blue by 35.5% and purple by 23.0%.	Foraging preferences and methods of prey capture influence MPs ingestion.	(Peters et al., 2017)
Malaysia	Dried fish	Edible tissues	Raman spectroscopy and EDX	Polymers 59.0% and pigments 21.3%.	1 to 3 MPs per fish	29 MPs and 9 pigment particles were isolated from the eviscerated flesh.	The most abundant polymers were PP 47.2% followed by PE 41.6%, PS 5.56%, PET 2.77%, and nylon-6 2.77%.	(Karami et al., 2017b)
French Atlantic coast	Blue mussel (*Mytilus edulis*) and Pacific oyster (*Crassostrea gigas*)	Soft tissues	μFT-IR	MP size ranging from 50 to 100 μm was about 50% of MPs for both species	0.61 ± 0.56 per mussel and 2.10 ± 1.71 for oyster.	Majority fragments and filaments. MPs in the mussels were gray by 51%, black, red, green 23, 11, 8 and 7% respectively.	Different sampling sites and different seasons, organism type had effect on contamination.	(Phuong et al., 2017)
	Fish larvae	Digestive tract	Microscope and FTIR		1.39 particles m^{-3}			(Steer et al., 2017)

(*continued on next page*)

Table 6 (*continued*)

Location	Microorganism	Accumulation part	Detection method	MP range/type	MPs concentration	Type/size/color of MPs	Remarks	Reference
Western English Channel, UK				66% of ingested MPs were blue fibers, mirroring trend for waterborne MPs.		MPs in fish consisted of blue or red fibers 83% and blue fragments 17%; fragments ranged from 50 to 100 μm in size, with fibers ranging from 100 to 1100 μm in length.	Ratio of waterborne MPs to fish larvae ranged from 27:1 nearest the coast, to 1:1 at 35 km from the coast.	
Great Barrier Reef	Green sea turtles (*Chelonia mydas*)	Foregut	ATR-FTIR	Particles ranging between 0.45 and 4.5 mm	–	Most particles were transparent and dark green.	Acid digestion followed by emulsification resulted in no significant change in the area of non-digested target polymers pieces.	(Caron et al., 2018)
Persian Gulf	Five littoral mollusk species	Whole body	Microscope and FTIR	Microfibres by 50% followed fragments by 26% were most common type.	0.2 to 21 particles per g of soft tissue	MPs were microfibres and fragments and colored in black, white, red, pink and green.	The dietary exposure of regional mollusk consumers of MPs, they have about 4800 MPs per capita per year.	(Naji et al., 2018)
Coastal waters of China	Mussels (*Mytilus edulis*, *Perna viridis*)	Whole body	Microscope	The abundance of MPs in mussels varied 0.77 to 8.22 items individual^{-1}	1.52 to 5.36 items g^{-1}	The most common type of MPs was fiber, followed by fragment and bead, PET, followed by rayon, PE, PVC and PP. PET was 74% in mussels	Mussels were more likely to ingest smaller rather than larger MPs.	(Qu et al., 2018)
Mondego estuary in Portugal	Commercial fish	Gastrointestinal tract	Stereomicroscope and (μ-FTIR)	30% of MPs had the larger size class (4–5 mm),	1.67 ± 0.27 item/fish.	Fibers Fibers 96% followed by fragments 4%. Majority were blue 47%, followed by transparent 30% and black 11%.	Fish species from the Mondego estuary are vulnerable to MPs contamination.	(Bessa et al., 2018)
Northeast of Persian Gulf, Iran	Benthic and pelagic fish species	Fish muscles	Microscope observation, SEM	MPs were identified as fragment, fiber, and pellet. The majority of the collected MPs were fibrous in shape.	5.66 to 18.5 items/10 g fish muscle	MPs were < 300 μm. And dominant colors were black, transparent and blue.	The relationship between metals (except Hg) and fish size is not clear and consistent.	(Akhbarizadeh et al., 2018)
Spanish Mediterranean coast	*Sardina pilchardus* and *Engraulis encrasicolus*	Gastrointestinal tract	Stereomicroscope and FTIR	Ingested fibers was 83% and PET was dominant by 30%	0 to 3 items/fish	Dominant colors were blue by 45.8% and transparent by 20.8%.	The relationship between MPs and natural fiber ingestion and sexual maturity was not significant	(Compa et al., 2018)

many detection techniques but there is a need for establishment of comparability of obtained results with these methods (Klein et al., 2018). Beer et al. (2018) suggested that to better understand about the impact of the MPs levels in Baltic environment, more data on the plastic retention times and potential releases of chemicals from the plastic particles should be obtained.

7. Conclusion

This paper complied the comprehensive information about importance of study on MPs pollution as a critical environmentally issue. In this regard, the following topics were discussed: a) Source of MPs, b) Detection methods and their pros and cons, c) MPs pollution in aqueous environments (marine, fresh waters and WWTPs), d) MPs pollution in biota e) existing gaps and recommendation for future works.

From literature it can be concluded that the sampling and detection of MPs in majority of studies in marine environment performed in sediment and some of them in water. In terms of color black, blue and white were dominant while PE, PP and fibers were major types of MPs. The range of MPs was between 3 and 150 items per/kg and the concentration of 2 to 100 MPs/kg of dry sediment. Mostly the researchers concluded that there was no significance difference between variety, abundance, number and types of MPs.

Different lakes and rivers had different types and level of MPs pollution. Similar to marine environment, PE, PP and fibers reported as major types of MPs in fresh waters while dominant colors were transparent, white and blue. In addition, variation in type and colors of MPs in freshwaters related to human activities. It can be concluded that the level of MPs pollution was high due to activity of residents and industries those were located near to fresh waters.

In terms of MPs pollution in biota, the majority of ingested MPs were accumulated in gastrointestinal tracts and stomach of biota. The number of MPs in biota was in the range of 1 to 20 items in different types of fishes. The dominant color of ingested MPs by biota was black and blue which majority consisted of fibers and fragments.

Based on the recent studies on MPs pollution in WWTPs, primary and secondary treatment can remove most MPs from wastewater, while tertiary treatment was not effective. Additionally, the removal efficiency ranged between 70% and 99%, while the remaining fraction is still a problem. Even after removing most of MPs, 0.25–1 MP m^{-3} may be present in effluent waters. Since large quantities of effluents are released every day, it is confirmed that effluents are responsible for the contamination of ecosystems.

Based on these investigations, following conclusion can be drawn:

1. Determination of particles by physical diffraction of the light as FTIR and Raman methods have limitation for small particle size.
2. Regulate some rules to mitigate the generation of secondary pollution which can be transferred to the marine as well as fresh waters.
3. Source-reduction based on banning certain plastic applications, such as microbeads in cosmetics products.
4. Substitution of some plastic products by biodegradable alternatives and improvement of worldwide waste management systems.
5. Better understanding of MPs fate by evaluation the residence time of MPs within the stomach and gut of biota.
6. Evaluation of MPs interaction with biota to prevent the associated problems which may threaten the future health.
7. More attention should be considered for the treatment or prevention of MPs pollution in WWTPs as they are associated to human directly.
8. Future studies should be directed towards prevention, awareness and reduction methods.
9. Researchers have to focus to stablish treatment techniques as the MPs detection is developed in satisfactory level.

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