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REVIEW

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Microplastic Pollution in Turkish Aquatic Ecosystems: Sources, Characteristics, Implications, and Mitigation Strategies

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Abstract

Aquatic environments are one of the final destinations for microplastics. In this review, a combination of systematic and narrative literature review was conducted to identify and summarise advances, gaps, and future directions in microplastic monitoring studies in the Turkish aquatic environment and in inhabiting aquatic organisms. A total of 62 peer-reviewed publications available on Web of Science were considered in the systematic review. Additionally, the current state of microplastic pollution in Turkish aquatic environments which includes marine and freshwater ecosystems, as well as aquatic organisms, and sources and characteristics of microplastics were reviewed narratively. Türkiye's position on the global plastic treaty and mitigation practices were also addressed. Although an increase in the number of publications over time was observed, the number and extent of studies carried out in freshwater ecosystems are limited. Strict legislation should be enacted and enforced to tackle plastic pollution in Türkiye. Additionally, nationwide, long-term monitoring studies at sufficiently regular intervals in aquatic environments should be considered.

1. Introduction

Since its invention more than a century ago, plastic has gradually evolved into an indispensable component of our daily life. Plastics are used across virtually all known sectors, including chemicals, energy, automotive, defence, aerospace, logistics, transportation, real estate, tourism, packaging, agriculture, etc., due to their numerous favourable characteristics, such as flexibility, durability, resistance to corrosion, low density, low electrical and thermal conductivity, etc. (Adam et al., 2021; Citterich et al., 2023; Jimoh et al., 2023).

While the worldwide annual plastic generation was 1.5 million tons in 1950, it exceeded 390 million tons in 2019 (Kumar et al., 2021). Approximately half of these produced plastics end up in the environment, affecting every layer of the ecosystem (water, land, and air) due to inadequate waste management (Manu et al., 2023; Ahmed et al., 2022).

Plastic pollution, which is highly prevalent, now ranks among the top global environmental concerns. The main issue with these materials, which have such extensive and impactful uses, lies in their post-usage disposal. Due to poor degradation coupled with overproduction, use, and disposal, plastic pollution has become a transboundary issue for ecosystems and human health (Prata et al., 2019).

Plastic pollutants can be defined in different groups based on their sizes, including megaplastics (>100 cm), macroplastics (25 mm–100 cm), mesoplastics (5–25 mm), microplastics (1 µm–5 mm), and nanoplastics (<1 µm) (Kershaw et al., 2019). Microplastics can also be categorised as primary and secondary, depending on their original form. Primary microplastics refer to plastics produced directly in microparticle form that are more closely associated with the pharmaceutical and personal care products industries and exhibit a range of particle types, including fibers, fragments, films, spheres, and pellets. Secondary microplastics consist of the gradual fragmentation or degradation of larger plastics (Figure 1) already present in the environment (Carlos de Sá et al., 2018).

Breakdown can take place through various processes, including hydrolysis in the presence of water, photodegradation from UV light, physical weathering in sediments/soils, (thermal) oxidation, waves, as well as biological degradation pathways by organisms (Adam et al., 2021). Microplastics can be further categorised based on their physical features, such as shape, colour, and size (Alak et al., 2022).

Microplastics exhibit prolonged environmental persistence (De Falco et al., 2018), prompting researchers to extensively investigate their behaviour in a variety of environments, including biota (Wang et al., 2021). The enduring nature of microplastics underscores their potential impact on ecosystems and human health. Microplastics constitute a diverse variety of particles with a propensity to absorb harmful pollutants (Fu et al., 2021).

Considering these pressing issues, understanding the extent of microplastic pollution in Turkish marine ecosystems becomes imperative. Identifying the sources, pathways, and impacts of microplastics on aquatic life is crucial for implementing effective mitigation strategies and conservation measures. By addressing this issue head-on, we can work towards restoring the pristine beauty of the Turkish coastlines and safeguarding the rich biodiversity that thrives within these waters. The increase in microplastic pollution has emerged as a pressing global environmental concern, transcending geographical boundaries and impacting aquatic ecosystems worldwide. In the context of Türkiye, a country characterised by its rich aquatic biodiversity and vital water resources, the issue of microplastic pollution holds significant implications for both the environment and human health. In this review, we delve into the complexities of microplastic pollution in Turkish marine ecosystems, exploring its origins, distribution, and potential effects on both the environment and marine biota.

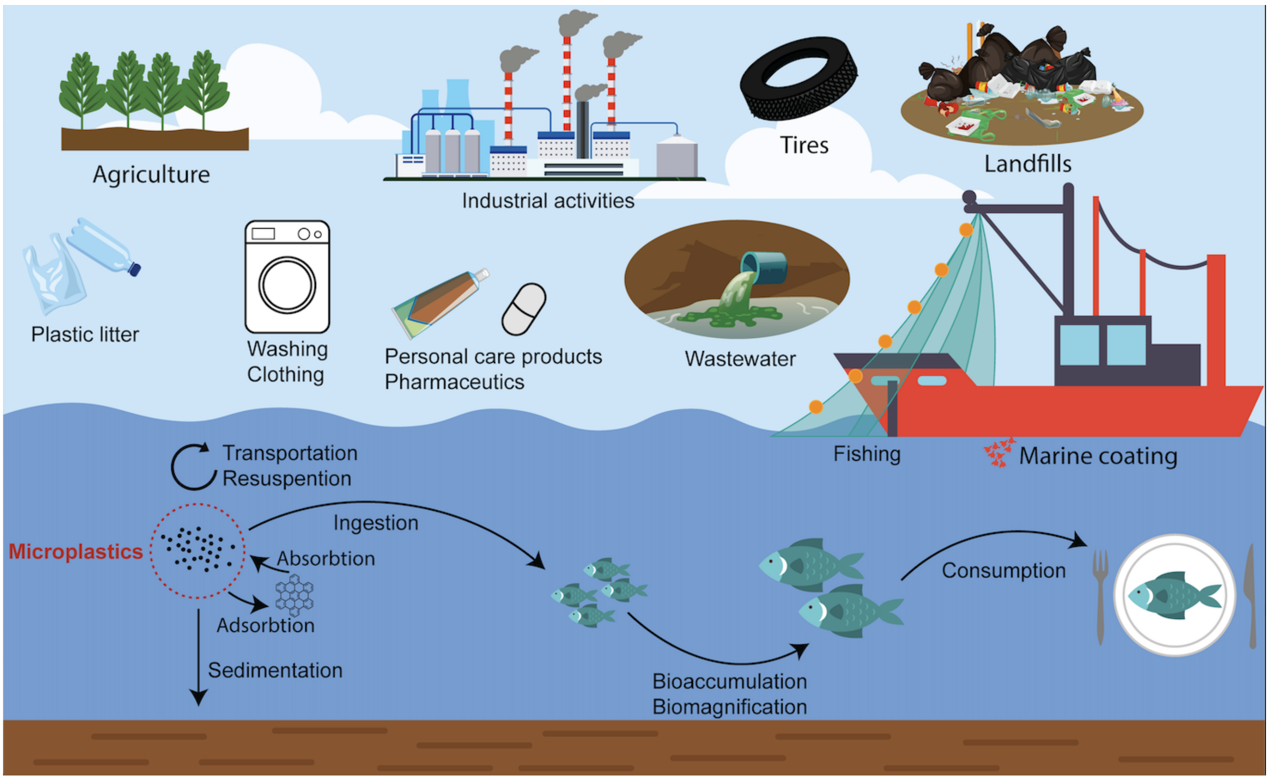

Figure 1. Main sources of microplastics and their fate in aquatic environments.

2. Bibliometric Details of Microplastic Research in Turkish Aquatic Environment

2.1. Literature Search and Review Protocol

A systematic literature search was conducted for existing peer-reviewed research articles using the Web of Science (WOS) database on August 28, 2023. The search strategy for this review was purely directed toward finding papers related to microplastic monitoring studies in Turkish aquatic ecosystems. A topic search (search in the title, abstract, and keyword fields) was conducted using the following search string: “TS=("micro$plastic" OR "microplastic$" OR "plastic$") AND TS=(pollut* OR monitor* OR digest* OR ingest* OR litter* OR occurrence) AND CU=(Turkey)”. A total of 585 articles were obtained from this search. As acknowledged, it is unlikely to find all the articles on microplastic monitoring studies performed in Türkiye, but the search results are likely to be representative of the majority of monitoring studies.

The article review process was divided into two consecutive steps: i) the article selection stage and ii) the data extraction stage. These two stages were performed by two reviewers. During the article selection stage, articles that focused on either microplastic monitoring in any aquatic ecosystem of Türkiye (sediment and/or surface water and/or water column samples from river and/or lake and/or dam and/or sea) or microplastic monitoring studies on aquatic organisms were included. Articles that were not in English, books, book sections, conference proceedings, review articles, modelling studies, experimental studies, and studies focused on wastewater treatment plants, air, soil, biotic or abiotic products were excluded. Of the 583 articles, 62 were selected for data extraction based on inclusion criteria.

Bibliometric data (title, author keywords, publication year, author names, author affiliations, journal names, etc.) of the articles selected for inclusion was retrieved from WOS.

Data (sampling coordinates, sampling environment, sample type, sampling site, detected microplastic abundance, type, size, shape, and polymer type) was manually extracted from each article to provide a comprehensive overview of the state of microplastic monitoring studies in Turkish aquatic ecosystems. For the studies that showed sampling sites on a map without providing geographic coordinates, approximate coordinates were assigned.

2.2. Data Analysis

The data cleaning and summarization processes were conducted using packages and functions from the *tidyverse* package (Wickham et al., 2019) of *R* (R Core Team, 2023). The collaboration network graph layout was calculated using the Kamada-Kawai algorithm from the *bibliometrix* package (Aria & Cuccurullo, 2023) and visualized using the *igraph* (Csardi & Nepus, 2006) package. The data for word clouds were prepared and visualised using the *tm* (Feinerer & Hornik, 2023) and *wordcloud* (Fellows, 2018) packages, respectively. To reduce noise in the word cloud, plural forms of the words were converted to singular forms (i.e. microplastics were converted to microplastic). Also, some of the locality names were standardised. The Sea of Marmara, Turkey, and Mediterranean were converted to the Marmara Sea, Türkiye, and Mediterranean Sea, respectively. The relationship between the publication year and number of publications was determined using the *lm()* function of base R. For the sampling station heat maps, 0.5x0.5 degree (55 km x 55 km) grids were created. The grids without sampling point(s) were excluded and sampling stations were counted within each grid area. The process was carried out using the functions of the *sf* package (Pebesma & Bivand, 2023).

2.3. Results of Bibliometric Analysis

Our search string found a total of 583 publications, covering original research articles, review articles, and book chapters (Supplementary Table 1). Of these, 62 (10.6%) peer-reviewed research articles conducted in Turkish aquatic ecosystems and/or aquatic organisms were included in this study based on the aforementioned criteria. The number of publications on microplastic monitoring in the Turkish aquatic ecosystems has significantly increased over time ($R^2 = 0.63$, $p<0.05$) (Figure 2A). These articles were published in 22 different journals indexed by the WOS. The journals Marine Pollution Bulletin (16 papers), followed by the Turkish Journal of Fisheries and Aquatic Sciences (7 papers), and Environmental Pollution (6 papers) had the highest number of publications (Figure 2B). The chord diagram revealed that there has been a rapid increase in the number of papers published in the Marine Pollution Bulletin since 2022 (Figure 2C). A considerable number of studies were published in the Turkish Journal of Fisheries and Aquatic Sciences in 2022. At least one paper from Türkiye has been published in Marine Pollution Bulletin and Environmental Pollution every year since 2017 (Figure 2C). Authors from 39 distinct institutions have contributed to microplastic studies in Turkish aquatic ecosystems. Four of these institutions were from foreign countries. With 17 papers, Recep Tayyip Erdoğan University has the most contribution, followed by Çukurova University (8 papers), Istanbul University-Cerrahpasa (7 papers), and Akdeniz University and Iskenderun Technical University (6 papers) (Figure 2D). A full list of the number of studies by institutions and journals is given in Supplementary Table 2 and 3, respectively. A collaboration network analysis revealed that Recep Tayyip Erdoğan University has the highest number of collaborations with other institutions. Among them, Karadeniz Technical University is the most

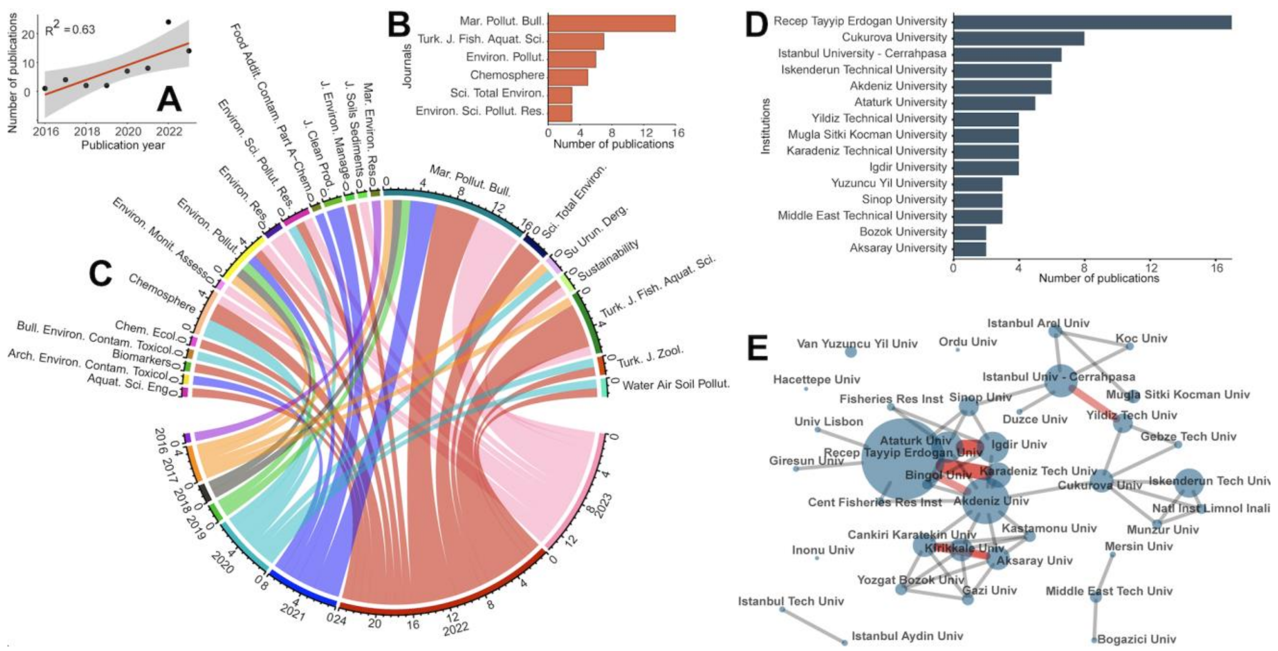

Figure 2. (A) The relationship between years and the number of published original research articles addressing microplastics in aquatic ecosystems and organisms in Türkiye. (B) The number of publications by journals (Journals with fewer than three publications were not given in the figure). (C) Chord diagram showing the distribution of publications by year and journal. (D) Number of publications by institution (top 15 institutions based on the number of publications are given in the figure). (E) Collaboration network between the institutions.

collaborative institution. On the other hand, Akdeniz University has the most diverse collaboration network (Figure 2E).

A word cloud generated from the words used in the titles of the studies revealed that the most common word in titles was microplastic, followed by Türkiye and pollution. In most of the studies, the authors defined the studied locality (i.e. the Mediterranean Sea, the Black Sea) and matrice (sediment, lake, fish, freshwater) in title (Figure 3).

3. Major Sources of Microplastic Pollution in Turkish Aquatic Environment

Since the initial investigation into plastic pollution in Turkish waters during the 1980s (Bingel et al., 1987), numerous subsequent studies have shed light on the seriousness of plastic pollution in this environment, stemming from various sources (Çevik et al., 2022; Aytan et al., 2020a,b). These studies have primarily focused on quantifying the presence of microplastics in different aquatic matrices (Güven et al. 2017). While some research has identified wastewater treatment plants (Akarsu et al. 2020; Vardar et al. 2021; Akdemir & Gedik, 2023) as a major pathway to microplastic contamination, others have pointed to riverine transport (Özgüler et al. 2022; Akdoğan et al. 2023). Urban activities (Sari Erkan et al., 2021a), agricultural practices (Gündoğdu et al., 2022), industrial activities (Almas et al., 2022), tourism (Gül, 2023) and sea-based sources (Çevik et al., 2022) are shown as potential sources of microplastics by many researchers.

3.1. The Transboundary Journey of Microplastics to Türkiye

In addition to plastic waste generated within Türkiye, microplastic pollution in specific regions along the Turkish coasts and inland waters has been attributed to increased plastic waste imports, particularly since 2018 (Gündoğdu & Walker, 2021). After China's ban on plastic waste imports in 2018, Türkiye emerged as a significant destination for the global plastic waste trade (Gündoğdu & Walker, 2021). Importing plastic waste from the European Union, the United Kingdom, the United States, and Japan in varying amounts. Moreover, recycling facilities involved in partial plastic processing have been identified as significant emitters of microplastics (Brown et al., 2023). The discharge of wastewater from recycling facilities, carrying a high microplastic load, is shown to be a major factor contributing to the escalation of microplastic pollution in aquatic environments in British waters (Brown et al., 2023).

Another contributor to plastic pollution in coastal areas is the transboundary plastic transport between countries by marine currents. Notably, investigations along the coasts of Sinop in the Black Sea (Oztekin et al., 2020) and Adana, Mersin, and Hatay in the Eastern Mediterranean Sea (Aydın et al., 2016; Gündoğdu & Çevik, 2019; Yılmaz et al., 2022) have reported a considerable presence of plastic debris of foreign origins brought in by currents. This raises the possibility that these sources could also contribute to microplastic pollution. This impact becomes particularly evident in

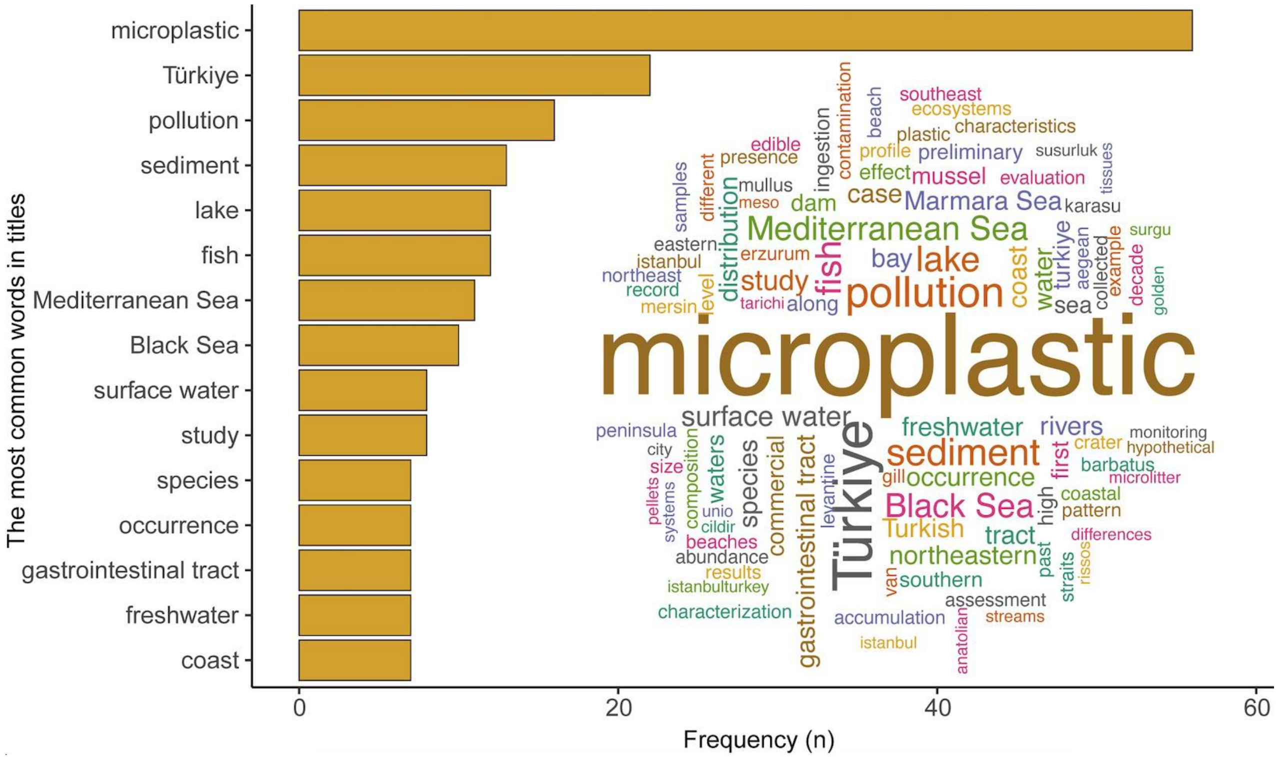

Figure 3. Frequency of the most common words in titles of published original research articles subjecting microplastics in aquatic ecosystems of Türkiye.

plastic pollution studies. Due to the combined effects of currents in the Black Sea and the Mediterranean Sea, a substantial amount of foreign-origin plastic waste accumulates on Turkish shores. Furthermore, intense ship traffic can occasionally bring foreign-origin plastic waste.

3.2. Sea-Based Sources (Fisheries and Maritime Transportation)

Approximately 10-20% of microplastics in the marine environment originate from a variety of sea-based sources, including fishing, aquaculture, maritime traffic (shipping, cruises, ferries, and other transport activities), coastal tourism, maritime coatings (application and maintenance, weathering), ports, marinas, shipyards (maintenance, weathering, dredging), and offshore industries (petroleum-related activities and wind farms) (Karbalaei et al., 2019). During surface preparation, coating application, and equipment cleaning, both commercial and recreational boats produce primary microplastics (OECD Series on Emissions Documents, 2009). Secondary microplastics could be derived from various maritime sectors as a result of maintenance, decommissioning, and wear/tear as well as the breakdown of large plastic items, including fishing and aquaculture equipment lost or discarded at sea from ships or offshore platforms (Law & Thompson, 2014).

There is limited information on the composition and quantities of microplastics released into the marine environment from sea-based sources. The majority of the fishing fleet in Türkiye is located on the Black Sea coast. Hence, fishing activities and shipping in coastal areas are among the primary sea-based sources of plastic in the Black Sea (Aytan et al., 2016; Terzi & Seyhan, 2017). The rivers in the Black Sea coast of Türkiye are also known to be the main route of plastic litter (Erüz et al., 2023). A number of studies have stated that fishing gear used in the Black Sea is one of the possible sources of microplastics (Eryaşar et al., 2021, 2022; Gedik & Gozler, 2022; Mutlu et al., 2022). The fisheries, aquaculture, and shipping activities were reported as major sources of marine plastic litter in Sinop, accounting for 25.8% of all litter found on the beaches (Bat et al., 2022). Plastic litter originated from fisheries and aquaculture was also found to be more prevalent on the beaches during fishing season in the south-eastern Black Sea (Öztekin et al., 2020; Aytan et al., 2020b). Similar to the findings of Bat et al. (2022), Terzi et al. (2020) also reported that 25% of the plastic litter found on the Black Sea coast comes from sea-based sources. The degradation of fisheries and aquaculture based plastic litter is a major microplastic source in the Black Sea. Moreover, ship paint fragments were also reported as a dominant microplastic in the surface waters (Öztekin & Bat 2017). The Sea of Marmara is a semi-enclosed basin that connects the Black Sea with the Aegean and Mediterranean Seas. Ports and harbours, heavy maritime traffic, and fisheries are important sea-based sources of plastic pollution in the Sea of Marmara (Topçu et al., 2013; Sivri et al., 2017). In a study conducted in the coastal waters of Küçükçekmece Lagoon, green microplastics increased twelve times in the summer compared to the winter season and mostly likely originated from green ropes used in fishing activities (Çullu et al., 2021). Paint particles were found to be the third most common particle, with higher concentrations at locations characterised by higher port/maritime activities in the Sea of Marmara (Gürkan & Yüksek, 2022). On the Aegean Sea and the Mediterranean Sea coasts, commercial ports, industrial zones, and yacht tourism were reported as important sources of high level microplastics on beaches (Yabanlı et al., 2019; Çevik et al., 2022).

3.3. Land-Based Sources (Wastewater, Agricultural Activities, Direct Littering, Industrial Activities)

According to Duis & Coors (2016), 80–90% of the microplastics detected in water bodies originate from land-based sources. These sources include various secondary microplastic items such as bags, bottles, personal care products, and clothing. Microplastics can enter the aquatic environment through sewage sludge and industrial activities, especially through the use of granules and small resin beads (Rolsky et al., 2020).

Small-sized plastics are commonly added to cosmetics or cleaning products as active carriers or ingredients and are also potential sources of plastic pollution (Kalčíková et al., 2017). Akarsu et al., (2022b) reported a high amount of microplastics (1000 particles /L) in the wastewater of a cosmetic factory located in Mersin, Türkiye. Recent studies have shown that washing machines are also an important source of microplastics (especially fibers), and it has been confirmed that fibers cannot be completely removed from wastewater, making laundries and the textile industry one of the main sources of land based microplastics (Akarsu & Deniz, 2021; Akyildiz et al., 2023).

Landfills serve as a commonly used waste disposal method, receiving substantial amounts of plastic waste. Although there is no study on the potential impact of landfills on microplastic pollution in Türkiye, a significant amount of microplastics is known to remain in landfill leachate treatment plants (Kara et al., 2022).

Wastewater treatment plants (WWTP) play a crucial role in treating wastewater from both civil and industrial sites. Although WWTPs are not specifically designed to retain microplastics, they can effectively reduce concentrations in municipal wastewater. Still, high microplastic concentrations in surface water samples close to WWTP discharge points were reported (Çullu et al., 2021). Despite their capacity to remove 55–97% of microplastics, Akarsu et al. (2020) calculated that the three wastewater treatment plants located in Mersin, Türkiye, release approximately 180×10^6 particles per day into Mersin Bay in the northeastern Mediterranean. Similarly, despite the high removal rates (85-93%) achieved by the Ambarlı WWTPs in Istanbul, an enormous quantity of microplastic particles (2.934×10^6 particles/day) were being released into the Sea of Marmara (Vardar et al., 2021).

4. General Characteristics of Microplastics in Aquatic Organisms: Types, Sizes, Colors, and Chemical Composition

In aquatic ecosystems, microplastics and associated chemicals can enter the bodies of organisms through various pathways: (i) absorption through the gills, (ii) ingestion through consumption (iii) direct adhesion of microplastics to organisms (de Sá et al., 2018; Öztürk & Altınok, 2020). Colours are thought to be effective in enhancing the selectivity features of microplastic particles by organisms. de Vries et al. (2020) and Güven et al. (2017) noted that fish exhibited a preference for microplastic particles in black and/or blue colour. This may be attributed to the comparatively higher prevalence of black and blue colours in the aquatic environment.

The levels of microplastics ingested by fish can be assessed using various protocols and methods (Lusher et al., 2017). While the use of 10% potassium hydroxide (KOH) solution for digesting organic matter in the gastrointestinal tract (GIT) is fairly prevalent (Lusher et al., 2017; Gündoğdu et al., 2020a), sodium hydroxide (NaOH) is also used in the application (Bellas et al., 2016; Baalkhuyur et al., 2020). Some researchers have suggested strong oxidant reagents such as sodium hypochlorite (NaClO) / nitric acid (HNO_3) (Reguera et al., 2019), hydrochloric acid (HCl) and HNO_3 (Santana et al., 2016) to achieve high degradation in biological tissues. Besides, because of their corrosiveness, using high concentrations of acid solutions reduces the recovery rate of most polymers (Lusher et al., 2017). The two common methods of separating microplastics from organic matter are the application of KOH and hydrogen peroxide (H_2O_2) (Schirinzi et al., 2020; Tsangaris et al., 2020). However, it has been reported that H2O2 concentrations of ≥30% degrade some polymers (Wagner et al., 2017), and there may be minimal modifications to the polymer spectra using a 15% H_2O_2 solution (Avio et al., 2015).

Microplastics differ not only in their chemical composition but also in the density, shape, and size of the particles. These features influence the behaviour, course, and mobilisation of microplastics in the medium. The assignment of microplastics necessitates reliable and fast analytical methods, usually divided into two steps: digestion/extraction of the organic fraction, and detection, characterization/quantification of microplastics. Various analytical techniques have been used to determine microplastics from different angles. Besides, none of this is comprehensive, meaning that two or more methods must be used to give a full insight into the properties of microplastics, especially when monitoring the activity of microplastics. Methods that can determine alterations in the structure of microplastics (based on chromatography and spectroscopy techniques) are more useful than those that provide insight mostly on surface and morphology alterations (based on microscopy techniques) (Miloloža et al., 2021).

When marine and freshwater studies are examined, it is thought that fiber microplastics are predominant, and potential sources for these plastics may be laundry, urban waste, and wastewater discharges. However, the high presence of fibers, in combination with some factors (physical, chemical, and biological) over time, can lead to the formation of much smaller particles. The size distribution of microplastics isolated from the investigated species differed between the studies. Microplastics of different size categories were identified in biota from aquatic ecosystems. There were significant differences in the size distribution of microplastics, and the microplastics counts increased as the particle size decreased. Fish selectively or unintentionally consume small microplastics, while larger particles are not retained in the gastrointestinal tract during ingestion and may be excreted in faeces.

5. Microplastics in the Turkish Marine Ecosystems (Beach, Sea Surface, Water Column, Sediment, Biota) with Respect to Microplastic Characteristics

According to the data retrieved from the included publications, microplastic monitoring studies in Turkish aquatic ecosystems were mostly performed in the marine environment (41 studies). Several of these studies were carried out in more than one sea, matrix, or taxon. The Mediterranean Sea was the most studied sea, with 15 investigations. Figure 4A display 14 studies from the Black Sea, 11 from the Sea of Marmara, and 5 from the Aegean Sea. With 21 publications, the focus was mostly on biota (Figure 4B). There were eight investigations focused on biota in the Mediterranean Sea, followed by the Black Sea (7 studies), the Sea of Marmara (4 studies), and the Aegean Sea (2 studies) (Figure 4B). Sixteen studies were conducted on seawater, with 7 from the Mediterranean Sea, 6 from the Black Sea, and 4 from the Sea of Marmara. There

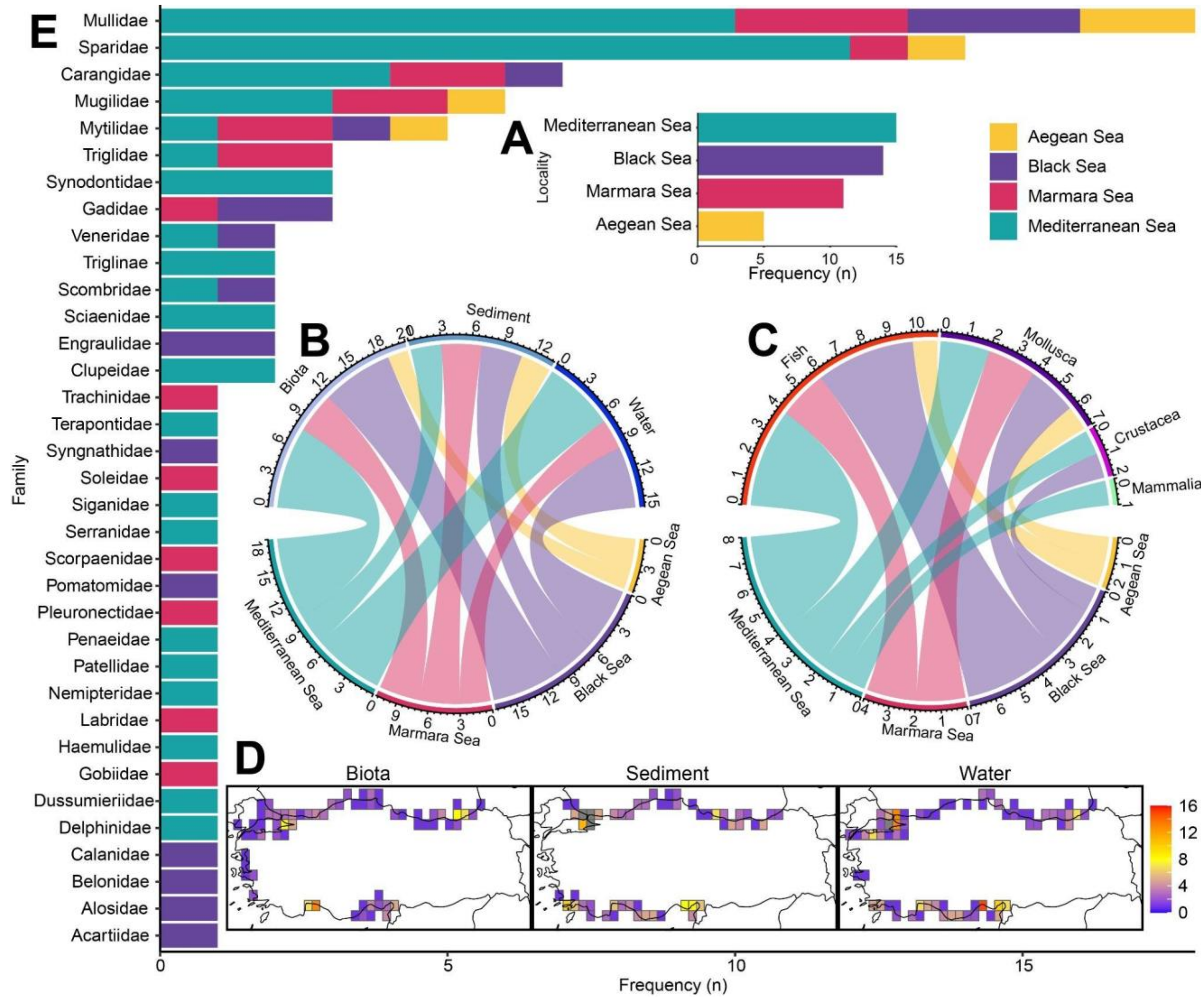

Figure 4. Distribution of microplastic monitoring studies in Turkish aquatic ecosystems by sea (A), sediment, biota, and water (B), studied organism groups (C), and studied families (E). The maps in panel D represent the number of sampling stations in each grid for biota, sediment, and water.

were 14 studies that focused on sea sediment (Figure 4B). Four studies were conducted in both the Black Sea and the Sea of Marmara, three studies were performed in the Aegean Sea and the Mediterranean Sea (Figure 4B). Fish were the most investigated group in the marine biota (11 studies), followed by mollusca (7 studies), crustaceans (2 studies), and mammalia (1 study) (Figure 4C). Furthermore, the only research on mammals was from the Mediterranean Sea (Figure 4C). The sampling station heatmap revealed that investigations in marine environments in Türkiye were mostly conducted along the coast (Figure 4D). There is a biota sampling gap in the Mediterranean Sea (Figure 4D). It is worth noting that a wide variety of marine organisms have been researched. The map was developed to highlight any gaps in the sampling effort. Although sediment and water sample stations have almost completely covered the whole coastline, there are still gaps in the Aegean Sea (Figure 4D). Mullidae (18 studies), Sparidae (14 studies), Carangidae (7 studies), and Mugilidae (6 studies) were found to be the most investigated families (Figure 4E). The studies on the aforementioned families were mostly performed in the Mediterranean Sea.

The marine microplastic research in Türkiye revealed a total of 28 distinct polymers. The most commonly reported polymers detected in Turkish seas were polypropylene (PP) (17 studies), polyethylene (PE) (17 studies), polyethylene terephthalate (PET) (15 studies), polyamide (PA) (12 studies), polyvinyl chloride (PVC) (11 studies), and polystyrene (PS) (8 studies) (Figure 5A). PP reported on six investigations from the Black Sea, five from the Mediterranean Sea, five from the Aegean Sea, and three from the Sea of Marmara. With 13 investigations from the Black Sea, 11 from the Mediterranean Sea, 9 from the Sea of Marmara, and 4 from the Aegean Sea, fragments were the most frequently reported shape (Figure 5B). Furthermore, fiber and film were reported in 34 and 27 investigations, respectively. Microplastics of sixteen distinct colors were reported in Turkish maritime ecosystems. The most commonly reported microplastic colors were blue (25 studies), red (23 studies), and black (22 studies). A

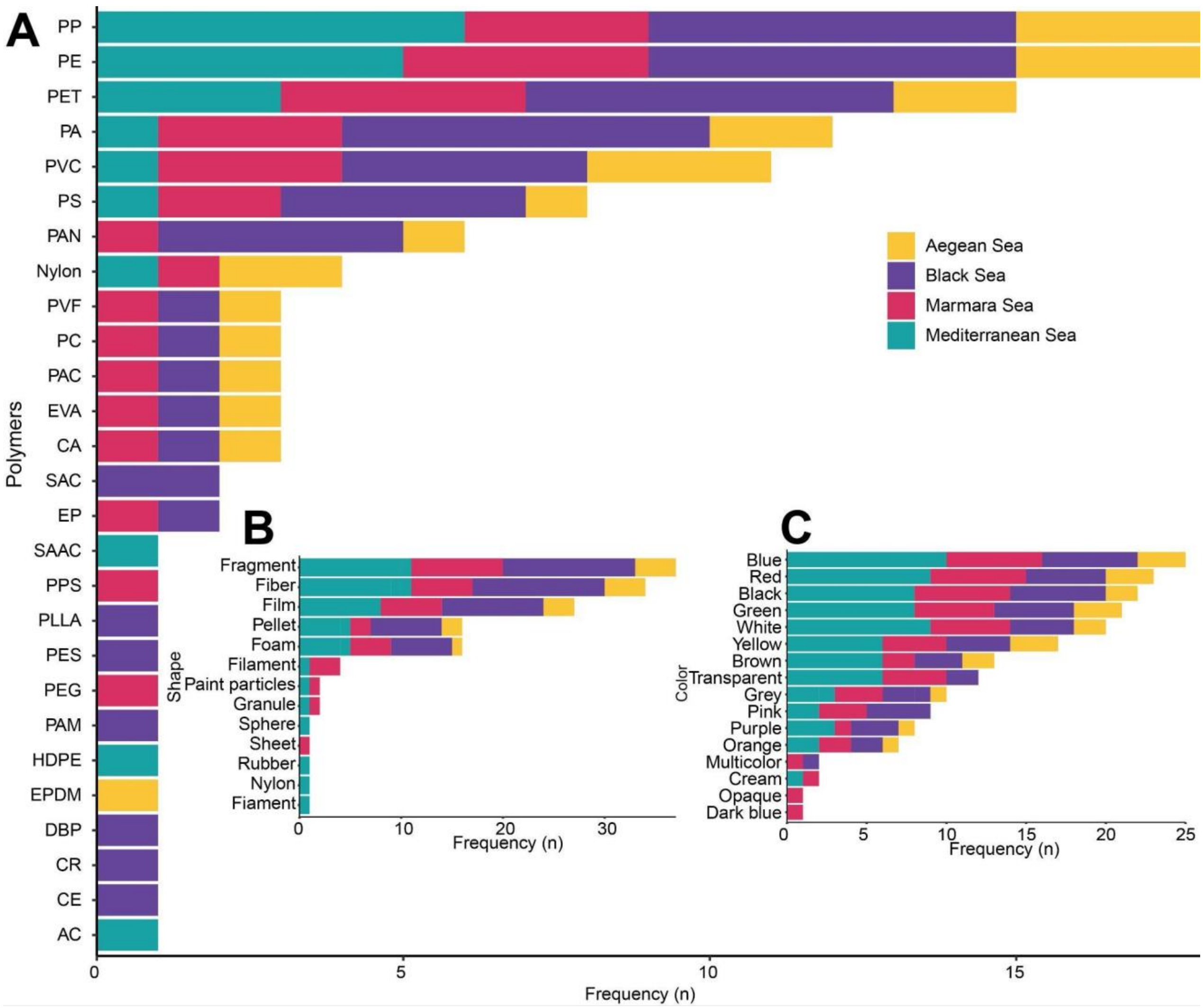

Figure 5. Distribution of the polymer types (A), shapes (B), colors (C) reported in microplastic studies from Turkish marine environments.

wide range of colors was reported in Turkish marine ecosystems.

5.1. The Black Sea

Being a landlocked sea and receiving a high load of freshwater input from the largest river systems of Europe, the Black Sea is considered as one of the most vulnerable sea environments in the world (Kideys, 2002; Pokazeev et al., 2021). In addition, tourism, marine activities, urbanisation, and agriculture in the coastal areas have a high contribution in pollution load. This surge in human activity brought an increase in waste generation, leading to significant pollution, with microplastics emerging as one of the major contaminants (Aytan et al., 2020a). They pose a formidable threat to marine coastal ecosystems, causing far-reaching consequences for both the environment and the organisms that inhabit these waters.

One of the primary contributors to the microplastic pollution in Turkish marine ecosystems is the haphazard disposal of plastic waste along the Black Sea beaches (Aytan et al., 2020b). The increasing influx of tourists during the summer months exacerbates the situation, leading to the accumulation of plastic debris that finds its way into the marine environment. Moreover, marine activities, sea transportation, domestic sewage discharge, and fishing practices add to the mounting burden of microplastic pollution in these sensitive ecosystems. Especially recently, floods from natural disasters on the Black Sea coasts have carried large amounts of plastic to these coasts. The journey of microplastics does not end when they reach the water column. Instead, these minute particles persist in the environment for an extended period, affecting marine life at various levels. Plastics can either float on the water surface, potentially being ingested by marine organisms like fish, seabirds, and turtles, or eventually settle on the seabed, embedding themselves into the sediment (Amelineau et al., 2016; Duncan et al., 2019). This dual nature of microplastics poses a complex challenge, as they not only cause immediate pollution in the marine environment but also pose a long-term threat to the delicate balance of marine ecosystems. The consequences of microplastic pollution extend far beyond aesthetic concerns. These minuscule particles have been found to act as vectors for harmful substances and toxins, posing severe risks to marine organisms (Okoye et al., 2022). When ingested, microplastics can obstruct digestive systems, lead to malnutrition, and interfere with reproductive processes, ultimately endangering the survival of marine species (Senko et al., 2020).

The extent of microplastic pollution along the Black Sea coast of Türkiye has been studied extensively. Studies have mainly focused on the determination of pollution states and impacts of microplastics in biota. To date, fourteen studies have been conducted on the Black Sea coast of Türkiye according to the latest Web of Science search. Four of these studies have been conducted to assess microplastic pollution in surface water (Terzi et al., 2022; Eryasar et al., 2021; Aytan et al., 2016). Terzi et al. (2022) conducted the most comprehensive microplastic monitoring study in the surface water and intertidal sediment (beach) throughout the Black Sea coast. Eryasar et al. (2021), assessed temporal changes in microplastic concentration in the surface water of the eastern coast of the Black Sea.

Few studies in the world ocean have reported microplastic contamination of plankton. Microplastic ingestion and egestion by zooplankton (copepods) which were collected from their natural environment in the Turkish Black Sea waters was reported (Aytan et al., 2022a). Copepods are the basis of the food web, favourite prey for many planktivorous fish and also having great function in marine biogeochemistry. Thus, occurrence of microplastics in these organisms from lower food webs provides evidence that zooplankton plays a vector role on the transfer of microplastics and associate chemicals to upper trophic levels including humans by contaminated seafood.

Micro, meso and macroplastics contamination in seven commercial fish species (*Engraulis encrasicolus, Trachurus mediterraneus, Sarda sarda, Belone belone, Pomatus saltatrix, Merlangius merlangus* and *Mullus barbatus*) in the Black Sea was investigated (Aytan et al., 2022b) and plastics mainly in the size of microplastics (93.2% of total plastics found) were found in 29% of gastrointestinal tract of all individuals examined (n=650). Microplastics found in GITs were mainly in the shape of fibres, colour of black and size of 1.84±2.80 mm. The main synthetic polymers found in GITs were PP (29.8%), PES (17.5%), acrylic (15.8%), PE (14%) and PS (1.8%).

In the recent study, occurrence of microplastics was reported in greater pipefish *Syngnathus acus* in the Black Sea for the first time (Senturk et al., 2023). Microplastics were found in 21% of total pipefish examined mainly in the fibres in shape (89%), black in colour (52%) and 0.2-1 mm (52%) in size. The mean concentration was 0.30 microplastic fish^{-1} (considering all the fish analysed) and PET (29%) was the most common polymer found in the gastrointestinal tracts of the pipefish analysed.

Plastics can serve as a substrate for microorganism colonisation and invertebrate assemblage formation which play a significant role in the fate of plastics by affecting the buoyancy, degradation, and toxicity of plastics (Zettler et al., 2013). Esensoy et al. (2020) assessed the microbial biofilm communities on the surface of plastics commonly used in daily life and fisheries, namely PE, PP, PET, PS, PA, nylon, and PVC in the Black Sea. This study showed that these plastics represent a new anthropogenic substrate in the Black Sea and become rapidly (within a week's) colonised by biofilm forming microorganisms.

5.2. The Sea of Marmara and the Turkish Straits

As in other seas and coastal areas of Türkiye, both anthropogenic (caused by human activities) and geogenic (occurring naturally in the environment) processes significantly contribute to the accumulation of microplastics in the marine ecosystem. In coastal regions such as the Sea of Marmara, where population and industrial development are intense, the combined action of tidal forces and density gradients influences the residence time of anthropogenic pollutants, leading to their prolonged presence in the environment. This extended exposure could have detrimental effects on the health of coastal organisms and human populations alike in the Sea of Marmara, as in other seas (Sivri et al., 2017; Chen et al., 2022). The study conducted by Sivri et al. (2017), is the first study in the Sea of Marmara that aims to determine the possible entrance ways of macro and microplastics into the marine ecosystem and their possible effects in the Istanbul coastal region and reveals the microplastics threat. This influence is particularly pronounced in specific water bodies characterised by concentrated anthropogenic waste and its status as an inland sea in the Sea of Marmara (Sivri & Çullu, 2020).

Numerous studies have investigated the occurrence of microplastics in the Sea of Marmara (Sivri et al., 2017; Tuncer et al., 2018; Vardar et al., 2021; Tan, 2022; Belivermiş et al., 2021; Akarsu et al., 2022a; Gürkan & Yüksek 2022; Sönmez et al., 2022; Akdoğan et al., 2023; İşlek et al., 2023; Sönmez et al., 2023; Olguner et al., 2023; Erkan et al., 2023). Microplastic abundance is influenced by the morphological features of coastal ecosystems (such as lagoons, barrier islands, tidal flats, barrier reefs, and sand dunes) and engineering constructions (such as breakwaters, groins, sea walls, and ports) (Çullu et al., 2021).

Taking into account the boundaries of the straits, the Istanbul Strait's entrance had more than two-fold microplastics in the water column compared to the exit of the Dardanelles (Gürkan & Yüksek, 2022). While the primary source of plastic pollution is often attributed to land-based activities, the contribution of plastic pollution from vessels should not be underestimated. Merchant vessels transiting through the Turkish Straits System (TSS) annually produced an average of 187.6 m^3 of plastic waste, roughly constituting 1% of the total waste documented along the TSS coastlines (Kaptan et al., 2020). Within the Istanbul Strait, microplastic abundance ranged between 144 and 700 microplastics per kilogram of dry sediment (Kaptan et al., 2020; Olguner et al., 2023).

Among the seven geographical regions of Türkiye, the Marmara Region has the second-smallest area, yet it has the largest population. In the centre of the region, the Istanbul, the largest city in Türkiye by population, which is also known as Türkiye’s industrial capital, is located. Istanbul, with a population exceeding 20 million, stands as the most densely populated city in the Marmara Region and in Türkiye, as well as the second most densely populated city in Europe. There are 87 WWTPs in Istanbul that primarily discharge into the Sea of Marmara, including the Bosphorus Strait, and into the Black Sea, which collectively have a total capacity of 5,881,660 cubic metres per day (Vardar et al., 2021). With this justification, it is normal that studies on MP are mostly focused on the coasts of Istanbul. Especially in the southern coastal area of Istanbul, where approximately 60% of the city's wastewater is discharged, the abundance of microplastics varied from 9 to over 1000 microplastics per litre (Sönmez et al., 2023). Other big cities of the Marmara Region are Bursa, İzmit, Balıkesir, Tekirdağ, Çanakkale and Edirne. Unfortunately, the scientific studies conducted in coastal areas of these cities are quite limited (Yenici & Turkoglu, 2023). Inconsistencies were observed among the studies performed in the Sea of Marmara in terms of microplastic abundance, possibly due to the different characteristics of sampling areas and differentiation in sampling and processing methods. For instance, Tunçer et al. (2018) reported an extremely high microplastic concentration (1263 particles/m^2) in the surface water of the Sea of Marmara, while Sarı Erkan et al. (2021a) found concentrations ranging between 0.27-3.49 particles/m^2. Additionally, Tan (2022) introduced a simple, fast, and practical multimetric index called the Microplastic Pollution Index (MPI). This index revealed that the highest MPI values were observed in the Izmit and Bandırma Gulf, while the lowest value was recorded at the inflow of the Dardanelle Strait.

Recently, there has been an increase in microplastic studies carried out in the sediment of the Sea of Marmara. As microplastics buried in sediments can interact with benthic biota, these particles can potentially also be used as a chronological tracer of sedimentary records (Simon-Sánchez et al., 2022). In the Golden Horn Estuary (Halic) of Istanbul, total plastic abundance was recorded as 566 particles/kg wet sediment (Doğruyol et al., 2019). Belivermiş et al. (2021) suggested that the Golden Horn Estuary was polluted with microplastics as early as from the 1950s, and the abundance of microplastics picked up in the 1980s. In the other area offshore near Pendik-Tuzla, the results revealed that all the sediment samples contained microplastics, and their concentrations ranged between 0.3 and 85.6 g/kg (Baysal et al., 2020). In the Istanbul Strait, the lowest amount of microplastics was detected at the Karaköy (144.4±77.9 microplastics/kg of dry sediment) and the highest amount was detected at the Anadolu Feneri (700±177.6 microplastics/kg of dry sediment) (Olguner et al., 2023). In the Sea of Marmara and the Bosphorus seabed sediment, the mean microplastic abundance was determined as 1957±4080 particle/kg (dry sediment) at all 43 stations, and the results indicated an overall dominance of microplastics having a size higher than 1 mm (Sarı Erkan et al., 2021b). It has been determined that there is limited research in sediment studies conducted in the Sea of Marmara outside of Istanbul.

In biota-related research, it is worth noting that the majority of studies focus on the Mediterranean mussels *(Mytilus galloprovincialis*), with reported values ranging from 0.08 to 7.53 microplastics/mussel (Gedik & Eryaşar, 2020; Gündoğdu et al., 2020a). When examining a total of 374 individuals from ecologically and economically significant fish species caught in the Gulf of İzmit, Türkiye, located in the Eastern Sea of Marmara, it was discovered that 147 individuals (39%) had ingested plastics. The average plastic ingestion was 1.14±1.03 microplastic per fish for the species *Trachurus mediterraneus, Chelon auratus, Merlangius merlangus, Mullus barbatus, Symphodus cinereus, Gobius niger, Chelidonichthys lastoviza, Chelidonichthys lucerna, Trachinus draco, Scorpaena porcus, Pegusa lascaris,* and *Platichthys flesus* when considering all the analysed fish (Aytan et al., 2023a). The corresponding value was 1.77±0.95 microplastics per fish when considering only those fish with plastic ingestion. The presence of microplastic fiber in the stomachs of the three male individuals of Mediterranean green crab (*Carcinus aestuarii* (Nardo, 1857)), was confirmed by Acar & Ateş, 2018. In controlled laboratory conditions, one investigation focused on the influence of microplastic consumption on the respiration and motility of the Marmara copepod, *Calanus euxinus* (İşinibilir et al., 2020). Similarly, in laboratory conditions, the potential impact of feeding habits on microplastic consumption and its adverse influence on the energy metabolism rates of two marine copepod species, *Acartia clausi* and *Centropages typicus* were studied (Svetlichny et al., 2021). Another study on the effects of polymers (PC, PET, and PBT), which are frequently used in personal care products and pharmaceutical products, on aquatic ecosystems, especially the cladoceran *Daphnia* sp., contains important data for the Sea of Marmara (Sönmez et al., 2020). İşinibilir et al. (2023) also studied the effects of microplastic beads (PS) on the survival, growth, and reproduction of *Daphnia* sp. The uptake and tissue distribution of both stressors (microplastics and mercury chloride) were examined in *Ruditapes philippinarum* (Sıkdokur et al., 2020).

Beaches in the metropolitan cities of the Sea of Marmara, especially, attract numerous tourists from around the world and serve as important ecological habitats for various life forms. Unfortunately, rapid urbanisation and industrial development have resulted in the excessive use of plastics, leading to increased plastic waste in the natural environment (Köklü et al., 2023). Studies in the Sea of Marmara region have focused on evaluating microplastic accumulation in beach surface sediments. However, most of these studies primarily address macro and mesoplastic pollution. A common finding in these studies is that PE types and additives dominate the composition of microplastics in all beach areas (Akarsu et al., 2022).

Lagoons play an important role in providing a variety of ecological services, including providing important habitats for several plant and animal species, including endemic species, and also acting as natural filters that regulate water quality. Also, these sensitive ecosystems can undergo rapid physical, chemical, and biological changes depending on the effects of environmental factors, especially anthropogenic processes. The global issue of microplastic pollution necessitates in-depth studies to comprehend its impact on socioeconomically and ecologically significant areas, such as lagoon systems (Bruschi et al., 2023). It is noteworthy that among the 36 large and small lagoons on the shores of the Sea of Marmara, the lagoon where the most research on microplastics has been conducted is the Küçükçekmece Lagoon. Among the studies on microplastic pollution in lagoons, the study conducted in Küçükçekmece Lagoon, which is one of the largest lagoons in Türkiye in terms of surface area, is a successful example. In Küçükçekmece Lagoon, microplastics abundance was notably higher than in other studied lagoons, with elevated concentrations detected in both the water (33 particles/L) and sediment (2922.32±517.35 microplastics/kg) (Çullu et al., 2021; İşlek et al., 2023). The microplastics distribution was different among sampling sites, being more abundant at sites in proximity to domestic sewage effluents and high levels of recreational activities (Sönmez et al., 2023). The chemical identities of the most common plastic particles found in the aquatic samples were PET, PE, PP, nylon, and PS. Some reported microplastics also contained heavy metals or other chemical pollutants absorbed from the environment, especially those microplastics collected from the lagoon and sediment samples. On the other hand, the cotton buds most frequently found in Küçükçekmece Lagoon contained higher levels of metals, specifically iron (Fe) and aluminium (Al), than those observed in the sediment of the lagoon. This implies that microplastics in the area may undergo a similar environmental fate with respect to these metals. Recent research indicates that interactions between microplastics and potentially toxic elements become more pronounced as the sampling location approaches the seafloor (Akarsu, 2023).

5.3. The Mediterranean Sea

Similar to most other marine environments, the Mediterranean coastline of Türkiye is also susceptible to the consequences of microplastic pollution. Additionally, the Mediterranean's partially enclosed nature contributes to a notable build-up of microplastics.

Scientific studies carried out on the Turkish Mediterranean coasts on microplastic assessments have focused mainly on the determination of pollution states and, to a lesser degree, on their impacts on biota. To date, more than twenty papers have been published evaluating the environmental pollution state, the impact of pollution on biota, and the pollution potential of wastewater treatment plants or rivers as a source on the Mediterranean Sea coasts of Türkiye. Half of these studies (including those on wastewater treatment plants and rivers) aimed to determine the pollution state, while the remaining half focused on examining the impact of the pollution on biota. Only one study used a different approach and assessed the pollution status and its accumulation in the biota simultaneously.

During the 2017-2023 period in which the microplastic studies took place, half of the studies focused on monitoring microplastics in seawater, sediment, and wastewater treatment plants along the coastline (Figure 2). Moreover, one modelling study was carried out to evaluate the spatial distribution of microplastic particles in Fethiye Bay (Genc et al., 2020) and the southeastern Black Sea (Yazır et al., 2022).

Studies on the impact of microplastic pollution on biota have been mainly conducted in the Iskenderun and Mersin Bays. Only one study has been carried out in Antalya Bay (Koraltan et al., 2022). Numerous species evaluated for the presence of plastic in the digestive system in studies. While most of the studies focused on examining microplastic digestion in fish, the rest of the microplastic studies on biota belong to the bivalvia (Yücel & Kılıç, 2023a), crustaceans (Yücel, 2023), and gastropoda (Değirmenci, 2022; Yücel & Kılıç, 2023b) groups. Furthermore, one study examined the gastrointestinal tract of a Risso's Dolphin, *Grampus griseus* which serves as a baseline for information on the relationship between cetaceans and microplastic pollution in the region (Yücel et al., 2022). Feeding strategy was reported to be a major factor that influences species vulnerability to microplastic pollution (Koraltan et al., 2022). In general, higher microplastic ingestion rates were reported in planktivorous organisms (Gündoğdu et al., 2020b; Güven et al., 2017; Kılıç, 2022a).

Additionally, previous studies showed that gills can also be considered as another pathway for microplastic entrance (Kılıç, 2022a; Kılıç & Yücel, 2022). However, previous studies reported lower microplastics abundance in the gills than in the gastrointestinal tract (Kılıç, 2022a). Moreover, available information indicates that the microplastic abundance in the water column and sediment is highly correlated with the microplastic ingestion rate of fish species. River discharge zones and İskenderun Bay were found to be the hotspots of micro and macroplastic litter in the Mediterranean Sea (González-Fernández et al., 2021; Gündoğdu et al., 2022b; Güven et al., 2017; Yılmaz et al., 2022). Into this, microplastic abundance in the gastrointestinal tracts of fish was found to be higher in these microplastic hotspot areas (Kılıç & Yücel, 2022; Koraltan et al., 2022).

In the context of studies aiming to assess the environmental state of microplastic pollution in the region, the quantities of particles in the sediment, water surface, and water column were identified. Out of these three environmental compartments, the water surface has received most of the attention. With the exception of one study that documented an increase in microplastic pollution in surface water after a flood event in the Eastern Mediterranean, reporting the presence of over 7.5 million particles per km^2 (Gündoğdu et al., 2018a). Microplastic pollution is shown to be rather high on the surface waters of the Mersin inner gulf and Iskenderun inner gulf regions. These regions have many freshwater inputs that are severely polluted with microplastics (Gündoğdu et al., 2018b). On the other hand, in contrast with the pollution levels observed in the eastern part of the Mediterranean, Antalya Bay experiences relatively lower pressure from sea surface microplastic pollution. It is worth mentioning that local hydrodynamic circulation patterns transport plastic waste from foreign countries and deposit it along the coastal regions of the northeastern Mediterranean Sea (Yılmaz et al., 2022).

Micro- and mesoplastic pollution is reported for the surface waters of the Finike (Anaximander) Seamounts, which is a high sea marine protected area in the eastern Mediterranean Sea (Aytan et al., 2022c). Microplastics were mostly fragments in shape, transparent in colour and 2-5mm in size and concentration of microplastics varied between $0.78x10^4$ to $73.9x10^4$ $par.km^{-2}$ (mean $19.2x10^4 \pm 26.7x10^4$ $par.km^{-2}$) and $0.13x10^4$ to $60.9x10^4$ $par.km^{-2}$ (mean $13.0x10^4 \pm 26.7x10^4$ $par.km^{-2}$) in May and September, respectively. In the surface waters of the Finike (Anaximander) Seamounts, the most abundant polymers were PE (69%). This study highlighted the urgent need to develop solutions for the problem of plastic pollution in the Mediterranean Sea.

Only a single study has been conducted to assess the condition of microplastic pollution in the water column within the region (Güven et al., 2017 Kideys et al., 2018a). The study encompassed 18 sampling locations within the Iskenderun and Mersin Bays. During the evaluation, it was observed that the Mersin inner gulf (3.5 to 16.7 particles m^{-3}) and the Yumurtalık (26.4 microplastics m^{-3}) region situated in the Iskenderun Gulf exhibited the highest levels of microplastic pollution, similar to the pollution state observed on the water surface.

Eleven scientific studies have been conducted to assess the influence of the local biota on pollution related to microplastics in the region. The evaluation included a total of 45 species, representing five different groups (Pisces, Crustacea, Gastropoda, Bivalvia and Mammalia), however, most of the studies focused on fishes (63.6%). Based on the findings of these studies, it was observed that the species primarily impacted by pollution were *Mugil cephalus* (9.6 - 46.4 particles $individual^{-1}$) (Kılıç & Yücel, 2022) and *Parapenaeus longirostris* (7.9 - 29.9 particles $individual^{-1}$) (Yücel, 2023).

There have been three studies conducted on microplastic pollution in sediment within the region. These studies include a comprehensive study on surface water and sediment throughout the Mediterranean Sea coast (Gedik et al., 2022), two that focused on beach areas (Gündoğdu et al., 2022a; Yabanlı et al., 2019) and one that examined sea sediment (Güven et al., 2017). It is important to note that these studies cannot be collectively evaluated due to their unique characteristics and methodologies. The assessments conducted by the state regarding microplastic pollution in beach areas (specifically plastic pellets) and seafloor sediments in Mersin and Iskenderun Bays showed a pollution state that is similar to what is observed in other environmental compartments. As a result, it can be concluded that the inner bay areas of Mersin and Iskenderun are also experiencing higher levels of pollution in terms of the presence of plastic in the sediment.

The microplastic discharge potential of eight wastewater treatment plants operating on the Mediterranean coast of Türkiye has also been determined. The most significant source of microplastic pollution in the region was reported to be the Karaduvar WWTP (more than 200 million particles per day), which operates on the border of Mersin province (Akarsu et al., 2020). The second important source was detected to be the Antakya WWTP (Kılıç et al., 2023). Another investigation elucidates that the Seyhan and Yüreğir WWTPs, responsible for the release of treated effluents into the Seyhan River—a significant tributary flowing into the Mediterranean Sea—constitute a noteworthy contribution of the Mediterranean microplastic pollution (Gündoğdu et al., 2018a). As stated in the literature reviews, plastic particles discharged from these sources to the natural environment are mostly fiber and the most dominant color was detected to be transparent.

6. Microplastic Pollution in Turkish Inland Water Ecosystems (Surface, Water Column, Sediment, Biota)

While the majority of earlier studies on microplastics primarily focused on marine environments, it has become increasingly evident that this issue is also of significant concern for freshwater environments (Gauquie et al., 2015; Auta et al., 2017). However, the number of studies in freshwater ecosystems is comparatively lower than that in marine ecosystems. A similar pattern also prevails for Turkish freshwater ecosystems (Çevik et al., 2022). Although there has been an increase in the number of studies conducted in freshwater in recent years, there are still geographical data gaps in Türkiye (Figure 6D). There are various studies carried out on the lentic (such as natural lake, dam lake, crater lake, pond, ditch, puddle, and reservoir) and lotic (such as river, riverine, and creek) ecosystems in Türkiye to determine the microplastic pollution in water (Atici et al., 2020; Atici et al., 2022), sediment (Karaoğlu & Gül, 2020; Gedik & Atasaral, 2022; Mülayim et al., 2022; Turhan, 2022) and aquatic organisms (Atici et al., 2021; Atamanalp et al., 2022a, 2022b; Turhan, 2022; Böyükalan & Yerli, 2023; Terzi, 2023a; Terzi, 2023b, Gündoğdu et al., 2023; Gündoğdu, 2023; Atici, 2022; Gedik & Atasaral, 2022; Atamanalp et al., 2023b; Mülayim et al., 2022; Yücel & Kılıç, 2022a; Kılıç et al., 2022; Kılıç, 2022b; Karaoğlu & Gül, 2020; Tatlı et al., 2022; Guven, 2022).

The number of studies on the inland ecosystems of Türkiye are significantly lower than that of the marine environment. Of these, 14 studies were conducted in lake/pond/dam, and 8 studies were conducted in rivers (Figure 6A). Some of these studies were conducted on more than one locality, matrix, or taxon. Similar to marine studies, most of the studies were conducted on organisms (12 studies), followed by water (10 studies), and sediment (6 studies) (Figure 6B). Among them, nine studies on biota, four studies on sediment, and 5 studies on water were from lake/pond/dam. The studies focusing on inland water organisms were mainly conducted on fish (4 studies), amphibians (2 studies), mollusca (2 studies), and crustaceans (1 study) (Figure 6C). Among them, only two studies on fish and a single study on mollusca were conducted in rivers (Figure 6C). The microplastic studies in inland ecosystems, especially the ones reporting microplastic abundance/distribution in sediment and water samples, were carried out in the north-eastern part of Türkiye (Figure 6D). These studies reported results from a total of 43 distinct localities. The family Cyprinidae was the most studied taxon with 2 studies from rivers and 4 studies from lake/pond/dam environments (Figure 6E).

Based on the top four most reported polymers, a similar trend in polymer types was determined in the inland environments and marine ecosystems of Türkiye. PP was found in seven studies, followed by PE in six, and PET and PA in three studies (Figure 7A). Fragments were found to be the most common shape (18 studies), with the majority of reports coming from lakes, ponds, and dams (Figure 7B). Red, blue, and transparent particles were the most commonly observed colours in microplastics (Figure 7C). In Türkiye, albeit in limited numbers, there have also been studies on detoxification agents to reduce the negative effects of plastics, which are now accepted as a stressor. In this sense, Atamanalp et al. (2023c) examined the therapeutic effect of hydrogen-rich water (HRW) in *Oncorhynchus mykiss* fed with PP+PE contaminated feed and reported that PP+PE caused toxicity in the tissue samples (gill, brain and liver) but HRW was effective in the ROS / GSH / MDA pathways in suppressing this toxicity.

Aytan et al. (2023b) reported, for the first time, the occurrence of micro-, meso- and macroplastics in an endemic fish *Alburnus sellal* and its parasite *Ligula intestinalis* in the Tigris River, one of the two large rivers that defines Mesopotamia. Plastics, mainly fibers, were found in 57% of *A. sellal* specimens and in 74% of *L. intestinalis* specimens. In both specimens acrylic (PAN) was the most common polymer as confirmed by FTIR spectroscopy.

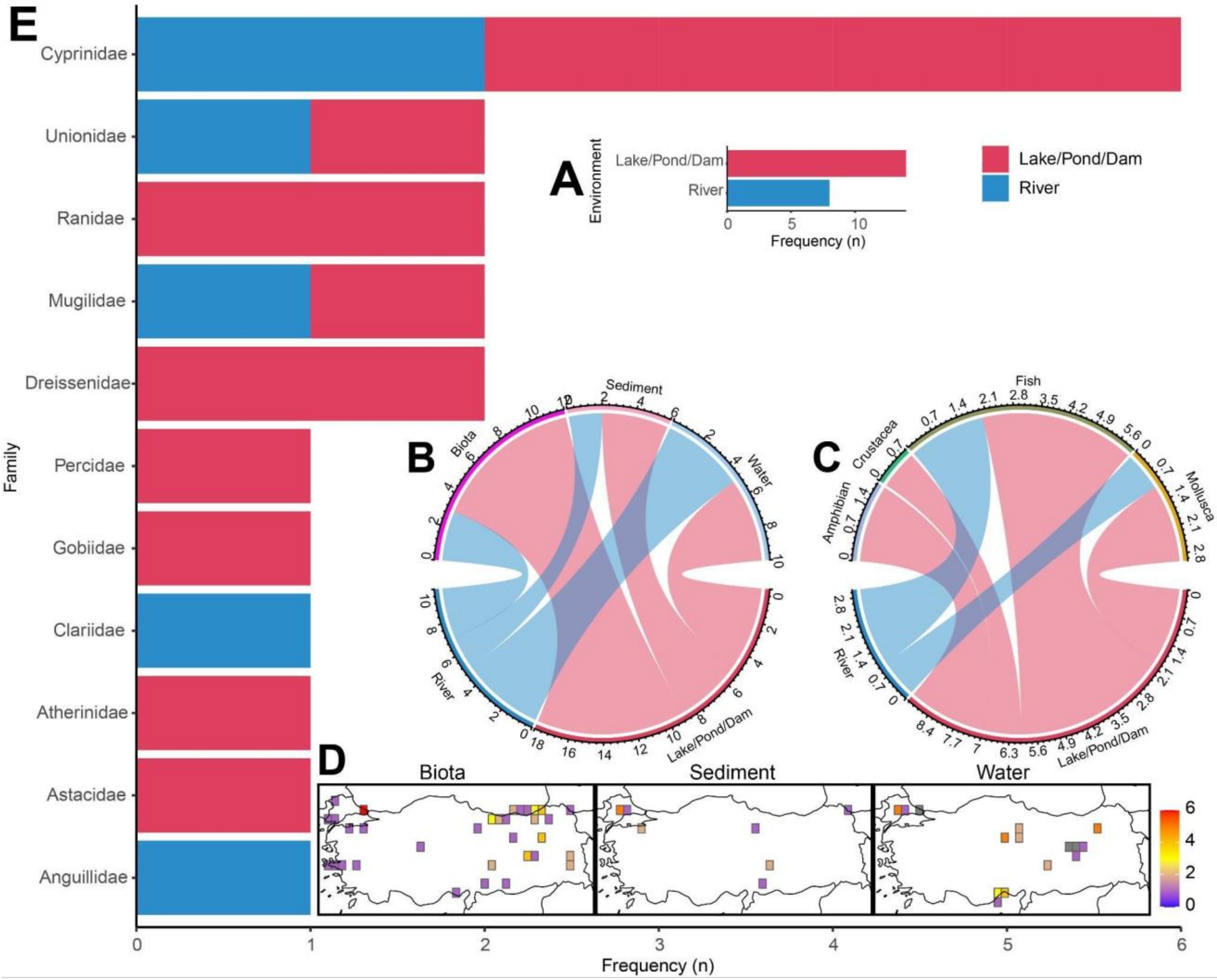

Figure 6. The number of published original research articles subjecting microplastics in inland waters of Türkiye (A), matrices (B), organism groups (C), and families (E). The maps in panel D represent the number of sampling stations in each grid for biota, sediment, and water.

7. From Water to Plate: Microplastic Transfer to Human Through Aquatic Foods

The World Health Organization (WHO) has great concern regarding the human health effects and exposure of nano- and microplastics. Inhalation, ingestion, and skin contact are the main ways of nano- and microplastic exposure by humans. Microplastic-contaminated food and beverages are considered the main routes to the human digestive system (Cox et al., 2019).

Because of their small size, microplastics can be bioavailable in a range of organisms at different trophic levels, including fish, bivalves, zooplankton, and marine megafauna and can be transferred along the food chain (Lindeque et al., 2020; Sfriso et al., 2020). In addition, processing, and packaging can lead to contamination of seafood with microplastics (Alak et al., 2021, 2022; Atamanalp et al., 2023a). Plastics are widely used in food packaging because they provide a good barrier of protection from microorganisms, moisture, and oxygen (Kedzierski et al., 2021). Besides, it has lately been reported that packaging can release microplastics and contaminate seafood with plastic particles (Alak et al., 2022; Alamdari et al., 2022).

Seafood provides roughly 20% of the animal protein source for nearly 3 billion people worldwide. According to Bitencourt et al. (2016), microplastics are reported to be present at levels of 7 particles/g for fish and 10 particles/g for shellfish, with particle sizes ranging from 0.13 to 5 mm. Heddagaard & Møller (2020) reported that an individual could potentially consume approximately 11,000 microplastic particles per year from such sources. Numerous studies have been conducted in Türkiye and other parts of the world to investigate microplastic contamination in aquatic food products. The main products studied are traditional stuffed mussels (Gündoğdu et al., 2020a), canned fish (Gündoğdu & Köşker, 2023), and table salt (Gündoğdu, 2018). The reported microplastic contamination levels in these studies suggest that Turkish consumers are under the threat of microplastic exposure through marine products, just like in other parts of the world. Studies reported that individuals may potentially consume

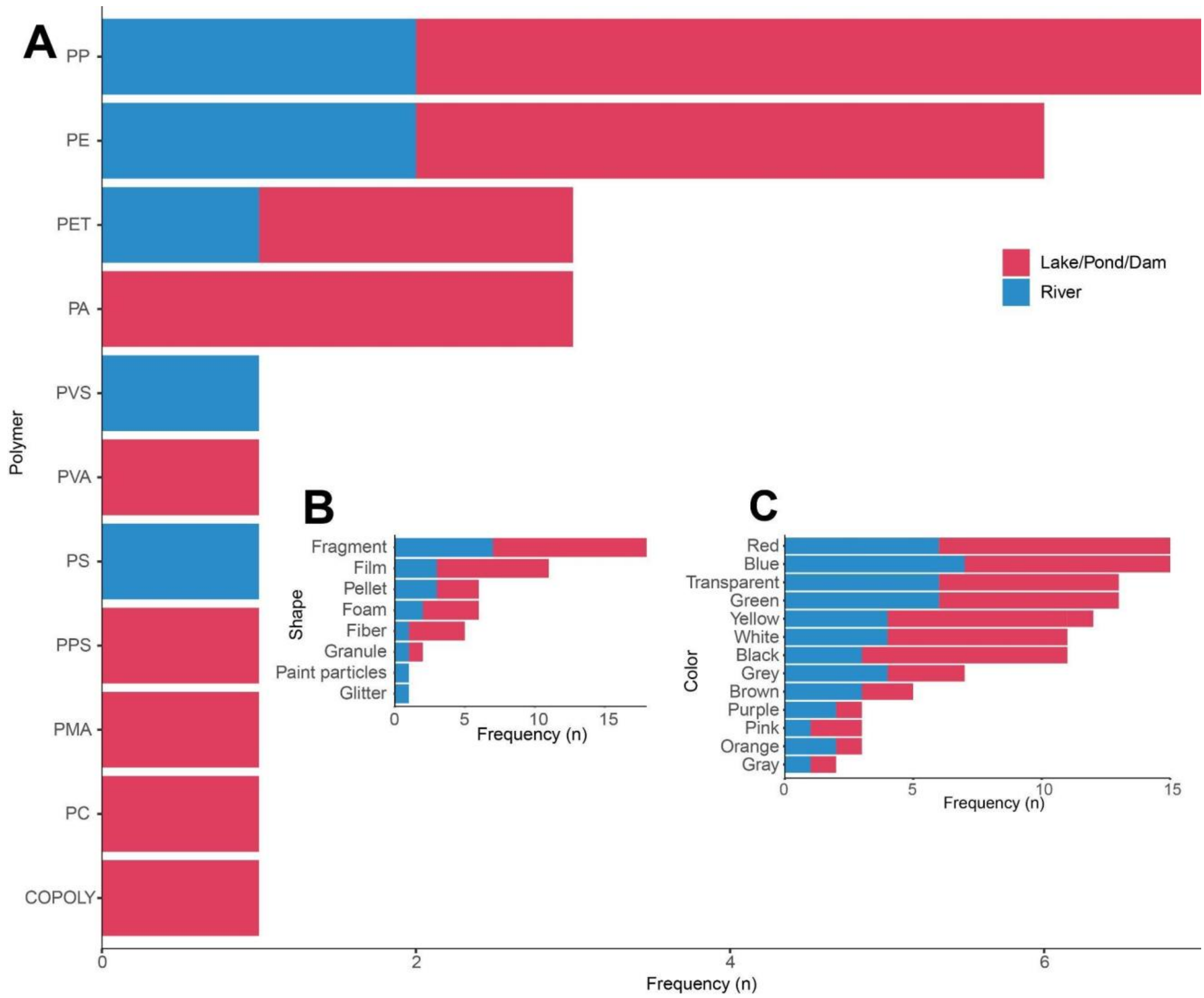

Figure 7. Frequency of the polymer types (A), shapes (B), colors (C) reported in microplastic studies from Turkish inland water environments.

approximately 48 microplastic per year (Köktürk et al., 2023) and 6140 microplastic per year (Alak et al., 2022) from aquatic sources in Türkiye. Although the consumption of sea-based food sources is currently low in Türkiye, the expected increase over time may lead to a higher risk of consuming microplastics.

The traceability of microplastics in contaminated seafood is crucial for understanding their bioaccumulation in the aquatic medium. It is difficult to assess the adverse effects of seafood consumption without appropriate information on the degree of diffusion of microplastics in the food chain (Carbery et al., 2018; Mercogliano et al., 2020). The potential impacts of microplastics on human health are largely dependent on the characteristics of the particles, and it is assumed that nanoplastics have more pronounced negative effects on human health compared to larger microplastics. Since the exposure methods for humans are ingestion and inhalation, the potential harmful effects can occur in the stomach, digestive system, and lungs (Rist et al., 2018). Microplastics are biologically persistent, and the ingestion of nanoparticles may lead to negative biological responses in humans, including inflammation, obesity, cardiovascular diseases, genotoxicity, infertility, oxidative stress, tissue necrosis, and cell apoptosis. As a result, they may be responsible for localised cellular and tissue fibrosis, damage, and potential carcinogenic effects (Nel, 2007; Miller et al., 2016; Sharma & Chatterjee, 2017; Lu et al., 2019; Ma et al., 2020). Furthermore, the presence of microplastics in the stomachs of commercially crucial fish species poses a risk to human health due to the potential transfer of these small plastic particles and/or associated pollutants to edible fish tissues, leading to potential effects (Fossi et al., 2018).

Microplastics can accelerate oxidative stress, induce changes in lipid and energy metabolism, and have neurotoxicological effects. A comprehensive assessment of microplastics should not only consider the levels of microplastics but also take into account their desorption and subsequent biological accessibility throughout the food chain, as well as the effects of food processing technologies on the concentrations of these pollutants (Carbery et al., 2018). According to this view, studies should focus on both the environmental pollution concerns of microplastics and the toxic effects of additives and plasticizers used during plastic production (Rist et al., 2018).

8. Global Plastic Treaty, a Legally Binding Instrument for Tackling Microplastic Pollution and Türkiye's Position

The widespread presence of microplastics in various environmental compartments, including biota, air, water, and sediment, is a consequence of their excessive production and generation (Casillas et al., 2023). Their small size and abundance make it nearly impossible to completely collect them once released into the environment. This escalating concern has not yet prompted a risk assessment for human and environmental health concerning biota (Rognerud et al., 2023). However, the time it takes for such assessments and corresponding measures to materialise allows microplastic concentrations to keep increasing, thereby heightening the risks they pose to both the environment and human health (Prata, 2023). Recent research revealing microplastics in human lungs (Jenner et al., 2022), placenta (Ragusa et al., 2021), breast milk (Ragusa et al., 2022), bloodstream (Leslie et al., 2022) and tumoral colon tissues (Çetin et al., 2023) further validates concerns about microplastic exposure's potential long-term health effects.

United Nations Member States are presently engaged in negotiations for a legally binding international agreement on plastics that will encompass the entire life cycle of plastic, including aspects like design, production, and disposal. International action under a global plastic treaty is imperative to address the transboundary nature of microplastic pollution, which can spread through natural routes like atmospheric dispersion and flowing currents, as well as plastic waste shipments (Rognerud et al., 2023). The root cause of microplastic pollution lies in the unsustainable production and consumption patterns of plastics, whether they are intentionally produced and used or formed through plastic material degradation. Various factors, such as chemical composition, integrity, and exposure to degradation forces determine the rate at which plastic products emit microplastics. While it is possible to reduce emissions through appropriate measures, it remains challenging to completely prevent all microplastic releases due to the inherent nature of plastic. However, implementing different control measures can substantially decrease release rates. These measures include phasing out unnecessary microplastic uses, reducing and eventually eliminating the production and use of non-essential plastic products, and placing a special emphasis on proper layout, use, and management of waste of both crucial and non-replaceable plastic items, microplastics, and plastic-based goods (Rognerud et al., 2023).

The complexity surrounding the assessment of microplastic accumulation and its environmental risks categorises microplastics as non-threshold pollutants for risk assessment (Koelmans et al., 2023). As a result, defining safe threshold values for microplastic emissions becomes an elusive challenge. Even if such thresholds were established, the persistent accumulation of microplastics in the environment would persist regardless of any reduction in plastic production and consumption (Rognerud et al., 2023). Consequently, any set threshold would inevitably be surpassed. This underscores the necessity for a precautionary approach to decreasing microplastic emissions through a comprehensive global plastic treaty targeting key pollution sources, including microplastics released from plastic product degradation. To achieve this, the plastic treaty should be grounded in fundamental principles of international environmental law, such as prevention, precautionary measures, and the polluter pays principle, with a legally binding framework in place (Bergmann et al., 2022). Encouragingly, the Intergovernmental Negotiations Meetings organised by the UN offer a glimmer of hope for resolving this pressing issue. The forthcoming international and legally binding agreement to combat plastic pollution, scheduled for preparation in 2024, relies heavily on government delegations as its foundation. This process also includes participation from industry representatives, non-governmental organisations, and scientists. However, a recurring concern is that obstacles hinder the effective involvement of scientists, posing a risk to establishing a robust decision-making mechanism rooted in scientific data (Carney Almroth et al., 2023). Government delegations are expected to actively engage in shaping the text of the agreement through extensive discussions on various solution scenarios, including national action plans to combat plastic pollution and formulating country policies based on the draft text. Notably, countries significantly impacted by microplastic pollution, especially small island states, underdeveloped or developing countries in the global south, and countries like Türkiye hold a prominent role. Türkiye's position is also crucial, as it faces plastic pollution from its own production and consumption and is affected by plastic pollutants originating from other countries. Türkiye can lead efforts to prevent plastic pollutants from entering the Mediterranean Sea by establishing a regional consortium. The forthcoming plastics agreement is set to introduce new international support mechanisms, leading to plastic-free the Mediterranean Sea and other Turkish coasts in the short, medium, and long term. Türkiye can take a leading role in this by proactively preventing plastic pollution at its source and developing scientific and technological infrastructure with the aid of emerging support mechanisms. Additionally, the plastic treaty presents an opportunity for Türkiye to transition from being a target country in the plastic waste trade, under the circular economy approach, to reducing and recycling its waste.

To effectively combat plastic pollution worldwide, a comprehensive global plastic treaty must specifically address microplastics as a distinct category of concern. This entails implementing targeted control measures to mitigate their impact. Türkiye should align with this approach, considering its own challenges with microplastic pollution and incorporating relevant strategies accordingly.

9. Recommendations on Prevention of Microplastic Pollution in Aquatic System in Türkiye

There is an increasing amount of research on monitoring microplastic pollution (Figure 2A) and its impacts on aquatic environments in Türkiye. To address the issue effectively, research efforts should prioritise closing knowledge gaps. Upon examining microplastic studies in Türkiye, several gaps and recommendations become evident:

- A substantial portion of the studies are limited in scope, often focusing on single time periods, leading to repetition and overlap. There are a limited number of studies concentrating on modelling, prevention, and establishing long-term trends. While relevant ministries conduct monitoring studies, the sampling points remain inadequate and restricted. Consequently, it is crucial to periodically conduct monitoring studies in critical ecosystems (such as lagoons, national parks, marine protected areas, etc.) to discern temporal trends in microplastic pollution. This approach can facilitate the development of preventive strategies.

- Increased collaboration between the institutions will pave the way for geographically comprehensive studies and development of standardised methods for monitoring microplastics in aquatic environments.

- The scarcity of studies identifying the sources of microplastic pollution poses a challenge to devising preventive measures. Thus, the creation of a national action plan is imperative. This plan would delineate sector-specific microplastic emissions based on results, allowing for the formulation of effective preventive strategies.

- Despite worldwide legal amendments to tackle microplastic prevention at its origins, Türkiye's lack of corresponding initiatives exacerbates the pollution problem and intensifies its challenges.

- Given the perceived high levels of microplastic pollution along Türkiye's Mediterranean and Black Sea coastlines as well as in inland waters, it is essential to implement measures targeting the elimination of primary microplastic sources. In this context, adhering to agreements like those of the European Commission, the Barcelona Convention, the Izmir Protocol, and the Bucharest Convention becomes crucial. It should also be noted that Türkiye is a candidate for full membership in the European Union (EU) and is hence trying to align its national legislation with that of the EU. The EU accession process necessitates that candidate countries are not only responsible for incorporating the EU acquis (body of EU laws and regulations) into their domestic legal framework but are also responsible for establishing the administrative and legal structures in charge of implementing the harmonised legislation. By taking these measures, it becomes possible to more effectively address the issue of microplastic contamination in the aquatic environment of Türkiye. Additionally, curbing illicit waste disposal practices and developing national waste management infrastructure are vital steps to address issues like plastic waste imports.

- The EU Green Deal and Circular Economy Action Plan demonstrate the European Commission's commitment to tackling microplastic pollution. The Commission aims to reduce microplastic pollution by 30% by 2030 as stated in the Zero Pollution Action Plan. As can be understood from the studies reviewed in this article, Türkiye faces a serious risk of microplastic pollution and, in this context, Türkiye should adopt the same short, medium and long-term pollution prevention plans as the EU. Therefore, Türkiye should implement similar legislation as the EU to limit the production and use of intentionally added microplastics (microbeads, glitter, artificial turf, etc.).

- By bolstering its position within the UN Plastic Treaty framework, assuming a regional leadership role, and actively engaging in the safeguarding of its neighbouring seas, Türkiye can make a significant contribution to the prevention of microplastic pollution.

- In the long run, an evaluation of the human health hazards posed by microplastics present in seafood should be monitored by Turkish officials. Presently, many developed nations have enacted legislation prohibiting the incorporation of plastic microbeads in personal care products. These regulations serve as crucial foundations for mitigating plastic pollution. The government bears the responsibility for overseeing the production, utilisation, recycling, and treatment of plastics to circumvent complexities and issues that could undermine all measures against microplastic pollution. Strict adherence to the principles of "extended producer responsibility" and "polluter pays principle" is imperative to enhance the efficacy of plastic recycling.

The ingestion of macro- and microplastics can have detrimental consequences for marine fish and wildlife. Consequently, it becomes imperative to curtail plastic consumption and promote recycling practices. Legislative measures aimed at curbing plastic pollution are equally essential for the preservation of the ecosystem. As a consequence, knowing the responses of global plastic contamination in aquatic ecosystem components at different concentrations will increase knowledge on microplastics and better correlate laboratory exposure surveys with actual ambient concentrations, helping to maintain food safety as well as environmental protection. The establishment of consistent research strategies in this regard will contribute to the commercial value of fishery products as well as human health.

10. Conclusions

Based on the articles reviewed in this study, it is clear that microplastics pose a major environmental problem for almost all aquatic ecosystems in Türkiye, as they do for the rest of the world. Numerous studies conducted on plastic pollution in aquatic ecosystems consistently highlight the importance of effective management of plastic waste, raising awareness, and implementing efforts to minimise the impact, all of which contribute to the sustainable use of plastic products. While the findings obtained in microplastic characterizations can provide information about the potential source of microplastics in aquatic environments, it is essential to recognize that the applicability of the results may be limited when dealing with microplastics in natural environments. Accordingly, innovative studies on long-term pathways of microplastic transport and contamination should be followed. Modelling such trajectories modifies our knowledge of their motion patterns, paving the way for more accurate analysis.

The presence of these pollutants in every component of the aquatic ecosystem, their transfer at trophic levels, and their impact on the presence of contaminants originating from raw materials or processes in all types of fresh-processed and semi-processed products, especially those for human consumption, need to be monitored.

Nevertheless, taking into account the data gathered from the literature review, adopting a holistic modelling approach for the migration of microplastics, and revealing the intricate interactions among various parameters would significantly contribute to enhancing food safety data and addressing an important gap in the data repositories related to this subject. Finally, awareness of this issue should be increased, and more effective studies should be carried out for the protection of the environment and human health.

Ethical Statement

This study does not require an ethics committee report.

Author Contribution

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Conflict of Interest

The authors declare that they do not possess any identifiable conflicts, whether financial or non-financial, professional or personal, which might be perceived as having an impact on the findings presented in this paper.

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Supplementary Table 2. The number of publications based on the affiliations of all the authors on the papers. If there was more than one author from the same institution on a paper, it was considered as a single record.

Institution	n
Recep Tayyip Erdogan University	17
Cukurova University	8
Akdeniz University	6
Iskenderun Technical University	6
Istanbul University - Cerrahpasa	7
Ataturk University	5
Igdir University	4
Karadeniz Technical University	4
Mugla Sitki Kocman University	4
Yildiz Technical University	4
Middle East Technical University	3
Sinop University	3
Van Yuzuncu Yil University	3
Aksaray University	2
Bozok University	2
Cankiri Karatekin University	2
Istanbul Arel University	2
Kirikkale University	2
Universidade de Lisboa	2
Bingol University	1
Canakkale Onsekiz Mart University	1
Consejo Nacional de Investigaciones Cientificas y Tecnicas (CONICET)	1
Duzce University	1
Gazi University	1
Gebze Technical University	1
Giresun University	1
Hacettepe University	1
Inonu University	1
Istanbul Aydin University	1
Istanbul Technical University	1
Kastamonu University	1
Koc University	1
Mersin University	1
Ministry of Food, Agriculture & Livestock - Türkiye	1
Munzur University	1
National University of the Littoral	1
Ordu University	1
Sevinc Erdal Inonu Foundation	1
University of Munich	1

Supplementary Table 3. The number of publications by journal.

Journal	n
Marine Pollution Bulletin	16
Turkish Journal of Fisheries and Aquatic Sciences	7
Environmental Pollution	6
Chemosphere	5
Environmental Science and Pollution Research	3
Science of The Total Environment	3
Environmental Research	2
Journal of Cleaner Production	2
Su Ürünleri Dergisi	2
Sustainability	2
Turkish Journal of Zoology	2
Water, Air, & Soil Pollution	2
Aquatic Sciences and Engineering	1
Archives of Environmental Contamination and Toxicology	1
Biomarkers	1
Bulletin of Environmental Contamination and Toxicology	1
Chemistry and Ecology	1
Environmental Monitoring and Assessment	1
Food Additives & Contaminants: Part A	1
Journal of Environmental Management	1
Journal of Soils and Sediments	1
Marine Environmental Research	1