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Sources, sinks and transformations of plastics in our oceans: Review, management strategies and modelling

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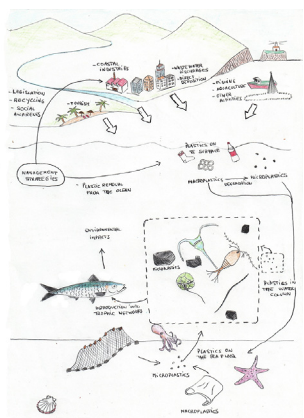
HIGHLIGHTS

- Current plastic management strategies in the marine environment are reviewed.
- A material flows analysis in different media of the marine environment is done.
- A model of the fate of the ocean plastics is developed and validated.
- Contribution to the knowledge of the fate and management of marine plastics.

GRAPHICAL ABSTRACT



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ABSTRACT

Currently, 60–80 % of litter is plastic, and almost 10 % ends up in the ocean directly or indirectly. Plastics often suffer from photooxidation producing microplastics and these microplastics derived from the breakdown of larger plastics are called secondary microplastics. These compounds simply cannot be extracted from the oceans, and once mixed, they enter the food chain and may have toxic effects.

This work reviews the current existing information on the topic in the scientific literature. Then, the current plastic management strategies in the marine environment are analysed, with the objective of identifying possible needs and improvements from a sustainable point of view, and to define new approaches. Simultaneously, a material flows analysis in different media of the marine environment is carried out using system dynamics. A preliminary model of plastics mobilization into the ocean to other media of the marine environment (like sediments and biota) is developed and validated with the existing data from the previous steps of the work.

This work expands the current knowledge on the plastics management, their transformations and accumulation in the marine environment and the harmful effects on it. Likewise, preliminary dynamic model of mobilization of plastics in the ocean is implemented, run, and validated. The developed model can be used to predict trends in the distribution of the plastics in the ocean with time. In addition, the most important reservoirs of plastics in the ocean can be observed. Although plastics undergo transformations in the marine environment, it is not a means of disposal since most of them are non-biodegradable. Most plastics accumulate on the seabed. The proportion of microplastics found in sediments is higher than that of macroplastics.

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1. Introduction

Plastic is a term that refers to a group of synthetic polymers (UNEP, 2015), and most of them are of petrochemical origin and derive from the polymerization of monomers (Waymanm and Nieman, 2021). Polymers are originated by different transformations of raw materials which 99 % come from fossil materials (crude oil or natural gas) (Nielsen et al., 2019; Petrochemicals Europe, 2019; ISO, 2020).

Plastics can have many classifications attending to different approaches. Resin Identification Coding System (RIC) is an international classification system based on its composition. RIC classifies plastics into seven categories: polyethylene terephthalate (PET or PETE), high density polyethylene (HDPE), polyvinylchloride (PVC), low density polyethylene (LDPE), polypropylene (PP), polystyrene (PS) and others (O). The last ones are nylon fibers, feeding bottles, compact discs, containers for medical use, car parts, etc. (ASTM, 2021).

Other classification can be attending to the size. Plastics with a size >25 mm are "macroplastics", "mesoplastics" have a size between 5 and 25 mm (Romeo et al., 2015). "Microplastics" correspond to plastics of <5 mm. Some authors also add "nanoplastics", a term under debate that has set the upper size limit at either 1000 nm or 100 nm (Gigault et al., 2018). To finalize the classification, microplastics according to their origin can be primary or secondary (Cole et al., 2011). Primary microplastics are those that add new micro-sized plastic material to the environment (Wang et al., 2019) and come from activities such as: medical applications, consumer products, agriculture, indoor particulate emissions, urban and transport infrastructure, intentional shredding and fragmentation plastic, processing industry, handling during manufacturing or maintenance (factories), abrasive media used at sea or coastal zone, coating or maintenance of plastic painted surfaces at shipyards or at sea or maritime sector (UNEP and GRID-Arendal, 2016). Secondary microplastics originate from the fragmentation of the macroplastics garbage in the environment (Wang et al., 2019).

After the 1950s, the use of plastic began to increase dramatically, due to its benefits for the health, safety, and energy of society (Schmaltz et al., 2020). In that moment the world had 2500 million people and the world production of plastic was 1.5 t (Aytan et al., 2020). Since 2004, as Fig. 1 shows, plastic production has increased considerably. The increase of plastic production since 2004 was from 225 million tonnes to 367 million tonnes in 2020 (Plastics Europe, 2022) and from 2012 plastic production increases 4 % annually (Jambeck et al., 2015; García-Rivera et al., 2017). The huge global production of plastics and its current great demand makes many scientists call our time as the "age of plastics" (Avio et al., 2017; Paiu et al., 2020).

Plastics are used from the automotive industry, packaging, and food to leisure, increasing the consumer dependence. Consequently, the demand for plastic products currently grows annually (Al-Salem, 2019). Loss of material value because of single use and low recycling rates, ill-effects on nature like climate and human health, are some of the problems of plastics (European Parliament, 2019). In 2014, the United Nations Environment Program (UNEP) identified plastic pollution as one of the top 10 emerging global environmental problems (Peng et al., 2020). It is estimated that plastic pollution causes $13 billion of financial damage annually (Nielsen et al., 2019). This is a big threat to marine and terrestrial ecosystems globally (Derraik, 2002), but nowadays, the focus is on marine pollution. According to Jambeck et al. (2015) in their Top 20, China, Indonesia and the Philippines are the countries that generate the most plastic marine debris.

Marine litter is a result of complicated waste management problems (Ahmad-Kamil et al., 2022) and it affects all the oceans of the Planet, from surface to seafloor, appearing in places as remote as the Artic or the Antarctica (Scotti et al., 2021; Parker, 2018). Parker (2018) used the map of *Jason Treat* drawing the distribution of marine plastic worldwide, the large accumulations of these materials, and the main rivers and land sources that transport these compounds to the sea. Marine litter composition can be made of infinity materials, although plastic is the more visual material due to its floatability (Velis, 2014) and colors. Plastic litter has always been recorded to be the most abundant marine litter compared with other types of marine litter (Galgani et al., 2015; Aytan et al., 2020; Ahmad-Kamil et al., 2022). Plastics are important due to its daily use and functionality because it is the most versatile material of modern times (Plastics Europe, 2022). Being cheap, lightweight, corrosion-resistant, elastic, and durable (Chen et al., 2021).

Regarding of marine litter composition, Galgani et al. (2015) affirmed that containers, fishing nets and their little parts, as well as small unidentifiable pieces of plastic represent the largest waste in marine litter, being the 80 % from land and 20 % from ocean-based activities (Schneider et al., 2022). Furthermore, these plastics are classified into three categories: plastics of fishing gear (27 %), single-use plastics (49 %) and other plastics (6 %) (European Parliament, 2021).

The objective of this work is to contribute to the knowledge of both plastic waste sources and plastics sinks in the ocean, plastics and microplastics transformations, and needs to the waste plastic management strategies, through a systematic bibliographic review and analysis. System dynamics is used to develop a dynamic material flow analysis, by the implementation of a preliminary multimedia modelling of plastics mobilization into the ocean to other media of the marine environment. This will be useful to predict trends and to identify new areas of study related to plastic waste accumulation in the oceans.

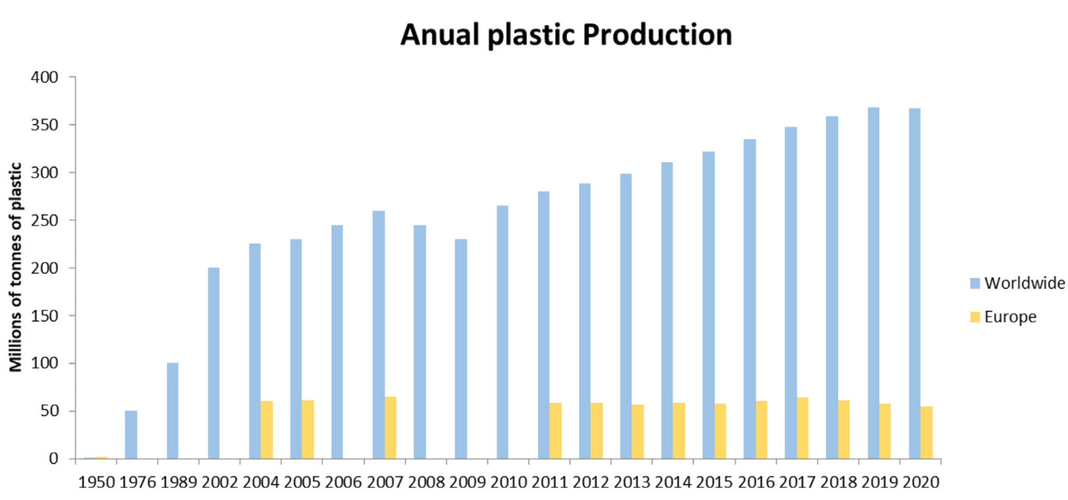

Fig. 1. Types of different plastic waste produced worldwide in 2015 (Own elaboration, data source: National Geographic, 2018).

2. Methodology

In this work, the applied methodology analyses the current problem of marine plastics. It consists of research work that analyses the background and state-of-art for marine plastics and the development of a model about the mobilization of the plastics in the ocean.

- To analyse the current problem of marine plastics, this work applies research, systematic review and analysis, identifying topics in the field, and classifying the works into them.
- Due to the dynamic nature of our system, system dynamics is used for studying and managing such as complex system which change over time, as a method of analysing problems in which time is an important factor. The dynamic problem studied is the accumulation of plastics in the marine environment: once plastics enter to the ocean, they distribute in different media. Multimedia dynamic modelling is developed implementing four model's phases increasing gradually the complexity. Models are used to predict trends of the system behaviour in a dynamic focus.

2.1. Review and study of the real system

2.1.1. Plastic marine litter review

Deep systematic research of literature is carried out to analyse how the problematic of plastic waste in the oceans is being addressed. In addition, this review provides an insight into the latest studies on this subject are focusing on. It is also used to collect data needed for research.

2.1.2. Management strategies analysis

An analysis of current marine plastics management strategies is developed, considering the information from the review.

2.1.3. Sources, sinks and transformations in the ocean

A small study to determine the origin of plastics, microplastics and the main sources and sinks in the oceans is done, considering the information obtained from the review. The transformations that these polymers undergo in the marine environment are also analysed.

2.2. Modelling of the plastics fate in ocean

After a previous deep review and analysis of existing models a preliminary model with four phases of the mobilization of plastics through ocean media (water, sediment and biota) are developed, focused on system dynamics using dynamic modelling. Models are used to analyse different scenarios obtaining the fate of the plastics (including macro and microplastics) in the ocean.

3. Review and study of the real system

An extensive review of scientific papers is carried out to identify those related to marine plastic waste, as well as its management strategies, or sources, sinks and transformations in the ocean.

The search is carried out using Web Of Science (WOS) database of the Spanish Foundation for Science and Technology (FECYT) under the Ministry of Science and Innovation. The searches were made selecting "all years (1900-2022)" in WOS to search all existing articles to date.

3.1. Plastic marine litter review

To review plastic marine litter, three searches with different initial parameters were performed. To the first search "marine litter" and "plastics" were used as a TITLE. In this search one of them was removed because it was a correction from another paper. To the second search "marine litter" as TOPIC and "plastics" as TITLE were used. In the second search also was remove another paper because of the topic does not correspond to the case study. The last search was "marine litter" as TITLE and "plastics" as TOPIC. After removing overlaps, there were a total of 978 scientist papers in the database of Web of Science about Plastic Marine Litter

The collected articles were classified into seven categories selected by different topics. Note that an article can belong to different categories dealing with various topics. The categories are: "macroplastics/mesoplastics", "microplastics/nanoplastics", "marine biodiversity", "management", "monitoring and modelling", "policy/social" and "spatial distribution". "Macroplastics/mesoplastics" group papers talking about large plastics in general, plastics that are over than 5 mm. "Microplastics/nanoplastics" group focus on studies about smaller plastic particles, <5 mm. The third category, "marine biodiversity" includes papers about the impact of macro and microplastics in different ecosystems or marine species. "Management" category contains articles of plastic waste management. "Monitoring and modelling" group includes papers that use monitoring and/or a model in its development. "Policy/social" is a category which includes social or political measures such as surveys, prevention programs or legislation. Finally, "spatial distribution" refers to spatial distribution of plastics in the oceans. Fig. 2, shows the articles per category and the relation between them.

The first study searched about the presence of marine plastics dates in 1978, based on observations made between 1972 and 1976 on beaches around New Zealand. The main concern in this study is virgin materials (Murray, 1978). Later, other authors as Winston, 1982 studies species that live in marine plastics moving through the oceans. Merrell (1980, 1984) published also the first works about plastic litter in Alaska.

Of the nine hundred and seventy eight papers analysed, five hundred and eight mention "macroplastics/mesoplastics" because many of them deal with marine litter in general and focus on large plastics, talking also about "microplastics or nanoplastics". The "microplastics/nanoplastics" include two hundred and sixty-four articles. Three hundred and seventy-three papers talk about the impact of plastics in "marine biodiversity" and a lot of them talk about plastic ingestion or entanglement in different species: sea turtles, seabirds (in special the genre *Fulmarus*).

Papers about "management" and "monitoring and modelling" have increased in the last year, one hundred and forty-nine and two hundred and sixty-seven respectively.

Fig. 2. Classification of articles in plastic marine litter review (own elaboration).

In the category "policy/social", there are two hundred and thirty-one papers that deal with citizen science, environmental education, and projects on surveys on marine litter and beach cleaning. Note that most political-social papers are focused on European politics being the marine strategy framework directive (Directive (UE) 2017/845/EC; Directive, 2008/56/EC) one of the most important.

Finally, in the last category, "spatial distribution", three hundred and seventy-five papers are found. These papers focus on the distribution of plastics in the different oceans and seas of the earth. There are many studies about the composition and distribution of plastic litter in the Mediterranean Sea and its internal seas such as Adriatic.

3.2. Management strategies

The category "management strategies" represents 15 % of the papers found in the review (one hundred and forty-nine papers). Although most of them do not specifically deal with marine plastic management, there are papers about management measures on land to prevent their arrival in the marine environment. While management strategies are essential to deal with the problem of plastic mismanagement, it is remarkable that it is the topic on which the fewest articles have been found.

Most of the articles related to the management of plastic in the oceans are reviews of the tools and legal frameworks that contribute to reducing the amount of plastic in the oceans. Although the first reports that deal with marine litter problems date back at the end of the 1960s, it was at 70–80s when most marine ecosystem threats were identified and the first policies were established (Ryan, 2015). Global policies are very necessary to reduce the production and consumption of plastic (especially single-use plastics) (Rangel-Buitrago et al., 2022). Currently, to address marine pollution problems, among other, there are three main international agreements: United Nations Convention on the Law of the Sea (UNCLOS), the International Convention for the Prevention of Marine Pollution (MARPOL) and the Convention for the Prevention of Marine Pollution by Dumping of Waste and Other Matter 1972 (London Convention) (Hsing-Hao, 2022). In addition, at the fifth United Nations Environment Assembly (UNEA-5.1) in 2021, the insufficiency of existing legal frameworks and international policies was insisted on due to the transboundary characteristics of plastics, supported by at least 40 countries (Sun et al., 2021). National policies are widespread throughout Europe based on the European Marine Strategy Framework Directive, 2008/56/EC and modified by Directive (EU), 2017/845, where all member states should have achieved Good Environmental Status by 2020 (MITECO, 2022). In Africa, Asia and Oceania they are increasing, in North America they are limited and they are seriously lacking in South America (Frantzi et al., 2021a).

Regarding other management techniques such as standard recycling based on mechanical reuse and recomposition, it is a technically inefficient and economically unfavourable method. Marine plastic debris is mixed, embedded with organic matter and contaminated with salts (Faussone et al., 2021). Still, there are works such as that of Veksha et al. (2022) investigated the technical and environmental aspects of marine plastic waste treatment, including the separation of PET for subsequent recycling. Faussone et al. (2021) tries to make diesel for boats from plastics found in the sea or Liu et al. (2022), who uses the calorific value of plastics found in the sea to fire ceramics in a mobile kiln installed in a boat.

Although there is no notification of many strategies to manipulate plastic in the oceans, there are projects such as Clean Atlantic (ongoing European project, whose purpose is to contribute to the reduction of the presence of marine litter in the Atlantic Ocean) (Interreg Atlantic Area, 2020). Ocean Cleanup is other project which is credited with building a giant plastic collection barrier in the ocean, and which works successfully in the Pacific Ocean (The ocean clean up, 2021). Citizen science campaigns are more present, such as the Spanish project about floating marine litter management *Libera, unidos contra la naturaleza* (Proyecto Libera, 2020). There are also projects such as the recent approved "Plastics monitoRIng detectiOn RemedIaTion recovery (PRIORITY)" (COST, 2021), a research network focused on developing, implementing and consolidating strategies to address the global challenge of environmental contamination by micro and nanoplastics.

3.3. Sources, sinks and transformations in the ocean

3.3.1. Plastic waste sources

The research to date reveals a large disparity between estimates of land-sources plastic debris entering the ocean and the amount of marine debris floating on the ocean surface (Ruiz et al., 2022). In 1975 the annual flow of litter of all materials (no data on plastic waste yet) to the ocean was 6.4 million tonnes (Jambeck et al., 2015). Nowadays exist an increase of data estimates, but even so there are no exact evidence of the quantity and origin of plastics present in the oceans (Jambeck et al., 2015). Currently, studies as Sherrington (2016) estimate 12.2 million tonnes of plastic per year that entering in marine environment. Furthemore in other studies state that almost 10 % of annual plastic production ends up in the oceans from various sources (Avio et al., 2017). Although in more recent studies Ritchie and Roser (2018), have estimated that 8 million tonnes of plastic entered the ocean in 2010 (3 % of the annual production of plastics that year). Other works show that in 2015 in the oceans there were 15–51 trillion pieces of plastic (93,000–236,000 t of plastic) (Peng et al., 2020). According to Peng et al. (2020) in 2017, the amount of plastic in oceans was >33 times of the total accumulated in 2015. In addition, Frantzi et al. (2021b) ensures that in 2050 there will be 33 billion tonnes of plastic in the ocean. Jambeck et al. (2015) estimated that in 2010, 192 coastal countries generated 275 million tons of plastic waste and between 4.8 and 12.7 million tons ended in the ocean. In addition, in their work estimated that at fifty miles from the coast, 99.5 million tonnes of waste plastic were generated, ending up to the ocean between 1.7 and 4.6 % in 2010. This data is understandable knowing that almost half of the population of the land resides in the fifty miles of the coast (Cole et al., 2011).

There are a lot of input sources of litter and plastics direct or indirect into the ocean (Fig. 3). The two main sources are: land sources (>80 % of the annual inputs) (Ryan et al., 2009; Sherrington, 2016), and ocean sources that are estimated a 20 % (Wootton et al., 2022). Land sources inputs can be coastal or inland and the most important are runoff from rivers, wastewater systems/sewerage, wind-blown litter and litter left in beaches (Ryan et al., 2009; Sherrington, 2016; Peng et al., 2020). Plastic particles can draw into the ocean from rivers because of a density lower or like water density (Peng et al., 2020). Sherrington (2016) estimates a mid-point of 0.5 million tonnes of plastics per year that come from rivers.

Rubbish dumped from ships, vessels and platforms, loss of packing and accidental releases is another important source of plastic pollution in the seas, and it represents 20 % (Li et al., 2016). Other important plastic source is fishing representing between 10 and 15 % of global marine litter by volume (Sherrington, 2016; UNEP and GRID-Arendal, 2016). Marine vessels during the 1970s dumped over 23,000 t of plastic packaging materials (Cole et al., 2011). Nowadays, 640,000 t of discarded fishing gear are added to ocean every year (Li et al., 2016). Currently an average of 1.75 million tonnes per year of litter from at-sea sources is estimated (assumption that 55 % by weight is plastic). Fishing and shipping dump 1.15 and 0.6 million tonnes of marine littler per year respectively (Sherrington, 2016).

Sources of microplastics and macroplastics to ocean are almost the same. Microplastics can enter to waterways through domestic or industrial drainage systems and wastewater treatment plants, straining through the filtration systems most of them (Cole et al., 2011). Sherrington (2016) estimates an average input of 0.95 million tonnes per year of primary microplastics to the ocean. The land sources of microplastics contribute 98 % in this input and the remaining 2 % come from ocean activities (Peng et al., 2020), while the macroplastics input to ocean from land sources is 80 % (Sherrington, 2016). Sherrington (2016) also groups the seven products that most contribute to the appearance of microplastics in the oceans: the vehicle tyre dust, pellet spills, textiles, building paints, road paints, cosmetics and marine paint.

Microplastics sources can be classified into sectors: producers (they can dump resin plastic granules), sectoral consumers (land-agriculture,

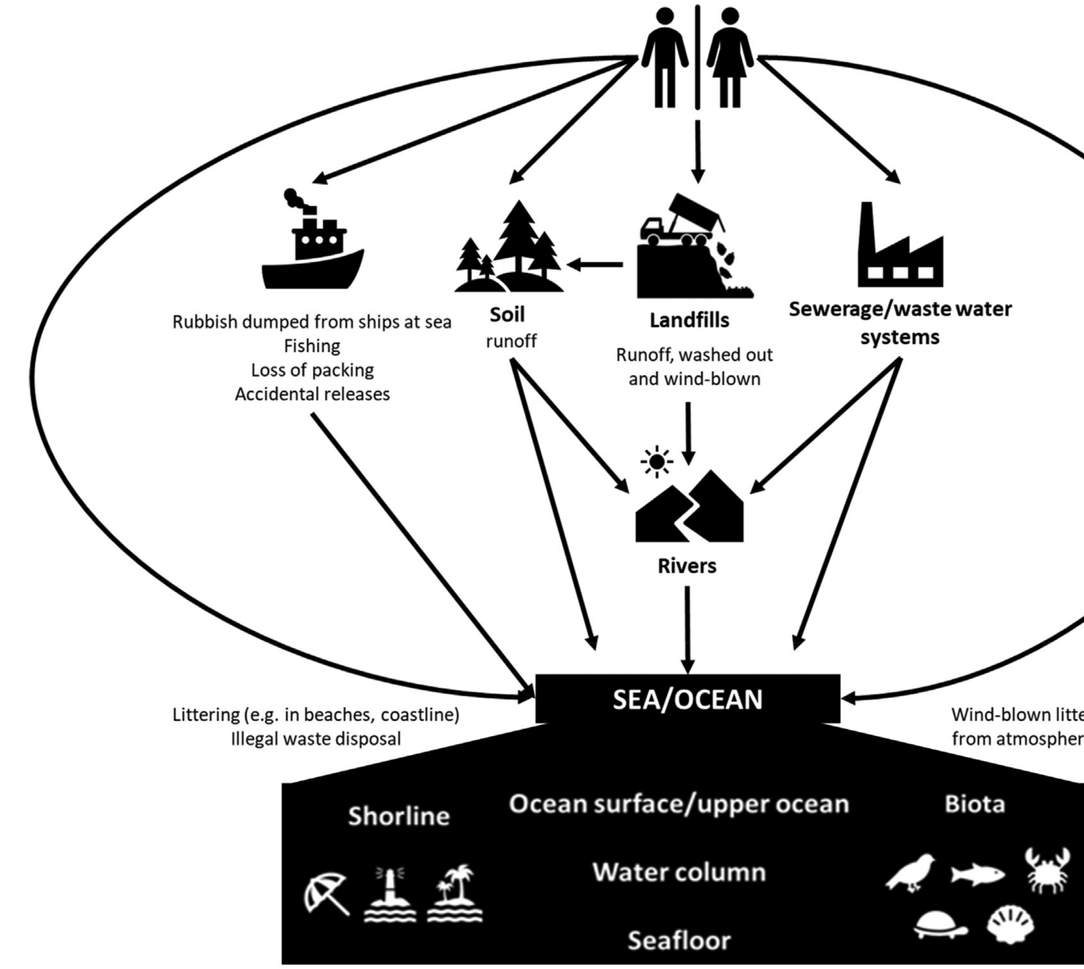

Fig. 3. Diagram of plastic waste source to the ocean and waste sink in the ocean (own elaboration).

construction, transport and leisure- or marine-fishing, aquaculture, transport and industry of high seas-), individual consumers (they dump plastics from food packaging, cosmetics or textiles) and, finally, waste management (GESAMP, 2015).

3.3.2. Plastic waste sinks

Depending on the composition of plastics, density and shape, they can be buoyant, neutrally buoyant or sink, distributing horizontally and vertically in the water column and in the seafloor (Cole et al., 2011). For example, polyethylene, propylene and many polystyrene foams are less dense than sea water and float, while vinyl chloride and polyethylene terephthalate sink (Andrady, 2015). The distribution also depends on other factors like winds, currents, coastline geography and human factors (urban areas, tourism and trade routes) (Li et al., 2016). In addition, due to their low degradation rates (it is estimated a range from 450 years to never), many of them remain in the ocean for decades (Parker, 2018).

In the marine environment, plastic slowly degrades into microplastics, and both macro and microplastics have been reported in multiple environmental compartments: surface waters, in the water column, sediments, sea ice and snow, the atmosphere and biota (killing each year thousands of fish, sea birds, sea turtles, and other marine species by ingesting or becoming entangled with plastic debris) (Kanhai et al., 2022; Dasgupta et al., 2022). Data of plastics in the different compartments are not very accurate and they vary in the different consulted scientific sources. Fig. 3 shows a diagram of plastic accumulation in ocean.

Considering marine litter in general, not just plastics, 15 % is floating, 15 % is in the water column and the remaining 70 % is on seafloor (García-Rivera et al., 2017). Most of the plastic waste in marine environment is deposited on the seafloor (94 %) and only a small percentage is on the ocean surface (1 %) (Sherrington, 2016). Although some authors say that plastics on the ocean surface are 0.5 % (UNEP and GRID-Arendal, 2016).

The amount of floating plastic, according to some sources is around 0.27 million tonnes (Sherrington, 2016), and the subtropical gyres are hotspots for plastics. The North Pacific Subtropical Gyre is one of the major hotspots of floating plastic on earth. There are also big accumulations in the South Pacific, North Atlantic and Indian Ocean (Parker, 2018).

On the seafloor are about 25.3 million tonnes of plastics being the largest amount of marine plastics. The most visible and easiest to sample plastics on the coastline are those found on beaches having an average of 1.4 million of tonnes of plastics (Sherrington, 2016).

Many of the macroplastics break down and accumulate in the form of secondary microplastics, adding to primary microplastics. These accumulate in the same places that macroplastics, in addition to atmosphere-ocean interface (GESAMP, 2015). The maximum concentration was found in the North Pacific Gyre, with 10 particles of microplastics per square metre (Sherrington, 2016). There are many recent studies that show the problem of surface plastics in closed seas such as the Mediterranean Sea. This is the most affected area in Europe, and it has the fourth highest concentration of floating litter in the world (García-Rivera et al., 2017).

Microplastics have been reported in marine sediments worldwide leading to the belief that the depths of the ocean will become a long-term sink for microplastics. Estimated accumulation of microplastics in sediments is important to identify probable areas of accumulation (GESAMP, 2015).

Plastic debris can accumulate in marine biota, especially by direct ingestion, but also by entanglement in packaging bands, synthetic ropes and lines, or drift nets (Parker, 2018). Therefore, biota also may represent an important sink for microplastics (Derraik, 2002). Ingestion of plastics (the majority microplastics) can affect to multiple species worldwide, being seabirds one of the most affected. Other important case is green turtles, which increased their plastic ingestion a 20 % in the period from 1985 to 2012, or the cetaceans increasing 11 times in number of affected since 1660 until 2010. This does not cause immediate death, although it generates adverse effects, leading to death (Li et al., 2016). Another form of accumulation of plastics in biota reported since 1800s is by plastic entanglement. Li et al. (2016), affirm in their study that entanglement is more frequent than ingestion.

"Missing plastics" are small quantities of microplastics that accumulate on Artic Sea Ice and the deep-sea sediments (Sherrington, 2016). Plastics leak from the ocean represents a 1.4–2.8 % (UNEP and GRID-Arendal, 2016).

3.3.3. Plastic transformations in the ocean

Although the interactions between plastic and microorganisms are poorly studied, it is known that oceans are not ideal disposal environments like composting or anaerobic digestion. Different plastic polymers, once they reach to the marine environment can undergo several transformations, resulting in the formation of secondary microplastic (GESAMP, 2015; Urbanek et al., 2018).

Degradation is the result of chemical changes in the structure of a polymer reducing its molecular weight. This is caused due to exposure to sunlight (photooxidation), but also by hydrolysis and biodegradation (Bond et al., 2018).

However, plastics can suffer fragmentation under abiotic factors (UV radiation, temperature, physical stress) for a long time, without decomposing or biodegrading (Urbanek et al., 2018). The 55 % of plastic waste on the coast corresponds to three polymers: high-density polyethylene, polypropylene and extruded polystyrene. According to Bond et al. (2018), these three polymers form microplastics after eight weeks.

Microplastics formation in oceans is influenced by many factors and depends on the polymer properties. Although there is not much information about the fragmentation of plastics in oceans, this is faster on the beaches followed by floating plastics, plastics in the water column and finally on the seabed. (GESAMP, 2015).

Marine biodegradability can be an important attribute for reducing the impact of plastic litter in the marine environment but varies between the different polymers (Al-Salem, 2019). Although biodegradation rate of plastic debris in the oceans is insignificant and it depends on the properties of the polymer, the biodegradable plastics will be more readily degraded (Li et al., 2016). Biodegradable polymers are degraded into small molecules such as CO_2, CH_4, and H_2O by the action of biota, but not all polymers with "bio" prefix are necessarily biodegradable (GESAMP, 2015).

Polymers like poly-Ɛ-caprolactone (PCL), polylactic (PLA), polybutylene succinate (PBS), poly-(butylene succinate-co adipate) (PBSA) or poly-(3-hydroxybutryrateco-3-hydroxyvalerate (PHBV) are considered biodegradable plastics. Otherwise, polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), polystyrene (PS) or polyvinyl chloride (PVC) are considered non-biodegradable because they can take decades to centuries to degrade (Urbanek et al., 2018). The best biodegradable polymer is polyhydroxyalkanoate followed by starch materials. Starch, suffer a degradation of 9 % in 49 days (checking in shopping plastic bags), completing degradation during long periods. Other polymers like polylactic acid are practically non-biodegradable. Still, the degradation time of polylactic acid is between 13 and 25 weeks, and degradation time of another polymer can be longer than 25 weeks (Müller et al., 2012).

Finally, other important data is that plastics can be a source of toxic chemicals in the environment. Many plastics have additives that end up in the environment, but this topic is not studied at all (Urbanek et al., 2018).

4. Modelling of the plastics fate in ocean

4.1. Review

In the plastic marine litter review, two hundred and sixty-seven papers were found over monitoring and modelling and more than half are published in the last two years. Only in the Most of them deal with macroplastics (ninety-four papers), although there are some that focus on microplastics (41 papers). Also, 38 of them are combined with the marine diversity category, 21 with social political issues and 20 with management at the same time. Most articles deal with the spatial distribution of plastics in ocean (137 papers) and they model their global distribution or the distribution in different oceans or located areas. The rest deal with input of plastic waste to marine environment (many from rivers), floating litter, monitoring, accumulation in different compartments of the ocean or accumulation in the ecosystems, and in marine biota.

Studies that analyse and model plastics in the sea are very frequent. In Maes and Blanke (2015), Maes & Blanke show that the traceability of garbage can contain information about ocean circulation. Bai et al. (2018) have created a model to forecast annual entry of plastics to ocean in China. For this, they perform an analysis of the material flow through the evaluation of the life cycle of plastic. Bruge et al. (2018) present in 2018 the results monitoring the garbage in 3 years in the Adour River basin (south-western France). On the other hand, Bauer-Civiello et al. (2019), estimate the plastics input in a river system through storm drains in a Tropical urban area. Van Emmerik et al. (2019a) analyses the variation of plastic transport through the Seine River according to the flow. In the same river, Tramoy et al. (2019), using the Jambeck statistical method, quantify the plastic flow with more precision. In 2019, the flow of river plastics originating in Jakarta was also estimated, using a combination of field measurements, empirical relationships, and hydraulic models (van Emmerik et al., 2019b). Cordier and Uehara (2019), focused on system dynamics, simulate scenarios designed to control plastic waste in the ocean. Turrell (2020) have performed simple models to predict the annual contributions of macro and microplastics to the Scottish coast.

Monitoring and modelling of marine debris worldwide are also a recurring topic, especially related to floating debris. In 2009, a review of plastics monitoring in the sea has been made to measure the changes in those wastes (Ryan et al., 2009). van Sebille et al., 2015, among other issues, aim to report the abundance and distribution of plastic debris in the ocean. Then, a study tried to identify the composition of the plastic materials found both on the coast and in sea turtles, through FTIR (Fourier Transform Infrared) spectroscopy (Mecozzi et al., 2016). In Hardesty et al. (2017), Hardesty, published an overview of the numerical simulation models that exist (based on ocean models), focusing on floating microplastics. These are key tools to obtain information about plastic distribution in the ocean. Working on the numerical modelling of plastic debris distribution, Liubartseva et al. (2018) establish a bi-dimensional Lagrangian framework to track transport and fate of plastics in the Mediterranean. Studies based on deep learning can be found to identify floating plastic marine debris (Kylili et al., 2019). These debris can be detected by geoinformation obtained from Unmanned Aerial Systems. Topouzelis et al. (2019), explore their viability. The marine research infrastructures are analysed by Conchubhair et al. (2019) with the aim of monitoring microplastics in the water column and quantifying their impact.

There are some studies about remote sensing of plastic litter using light reflectance of plastics floating (Goddijn-Murphy and Dufaur, 2018), monitoring floating macroplastics globally (Goddijn-Murphy et al., 2018) and studying Thermal Infrared Remote Sensing (Goddijn-Murphy and Williamson, 2019).

Many of the papers focus on the Mediterranean Sea and their internal seas, as well as floating litter too. In 2017, a floating marine litter transport model was built/developed using historical Lagrangian data from the Mediterranean Sea (Zambianchi et al., 2017). Crosti et al. (2018), have done a monitoring of floating garbage with a fixed observation point located in rivers near the sea. A global plastic transport model is also carried out in the Mediterranean Sea (Liubartseva et al., 2019). Franceschini et al. (2019) use artificial neural networks to model the effect of environmental descriptors on the distribution of litter, estimating the amount of marine litter in the Central Mediterranean Sea (Franceschini et al., 2019) Moreover, Castro-Jiménez et al. (2019), estimate the floating macro-garbage in surface waters of the Rhone River.

Other locations used as case studies were for example The North Pacific Gyre and Kuroshio current, Wang et al. (2010) performed a follow-up model. A monitoring study was developed on the Baltic seabed (Zablotski and Kraak, 2019). The PELETS-2D Lagrangian Model is used in the North Sea for a transport simulation (Neumann et al., 2014). In the same sea, a distribution and accumulation of plastic model was found (Stuparu et al., 2015). The floating marine litter transport and stranding were studied in the French Riviera (Ourmieres et al., 2018) and in the Iberian Northwest. In the last place, the work tracks particles to analyse the effects of winds on the floating marine litter transport (Pereiro et al., 2018). A Lagrangian particle tracking tool is also used with high-resolution ocean circulation models in the Easter Island ecoregion (Gennip et al., 2019). With these high-resolution models, the quarterly variability of floating plastic was analysed in a protected area of Menorca (Spain) (Ruiz-Orejón et al., 2019). In the Black Sea, Lagrangian simulations are used to study floating marine litter concentrations (Stanev and Ricker, 2019). The transport and accumulation modelling of floating microplastics has also been studied in South Africa (Collins and Hermes, 2019). Finally, in Bahía de Banderas (Mexico) the seasonal variation in the abundance of floating plastic was monitored (Pelamattia et al., 2019).

The distribution and accumulation of plastic on the beaches is an issue that groups several found works. The first work of this group monitored plastic on beaches classifying waste into categories (de Araújo et al., 2006). In 2009, another work on plastic accumulation and its exposure to UV radiation and physical processes was published (Corcoran et al., 2009). Kataoka et al. (2013) analyse a beach as a linear garbage entry/exit system. In the marginal seas of East Asia, a prediction of the amount of plastic on beaches is made every ten years (Kako et al., 2014). Plastic detection programs have also been performed on beaches (Lavers et al., 2016). Fannini and Bozzeda (2018) addressed the dynamics of resin pellet deposition on a Mediterranean beach. In addition, there are papers that use linear models to create an application that predicts marine litter on beaches (Hérnandez-González et al., 2019). Finally, the creation of a marine debris map using an Unmanned Aerial System has been published (Gonçalves et al., 2020).

A little group modelled the accumulation of plastic in the marine ecosystems and biota. To start, the plastic impact on megafauna of Saronikos Gulf, in Aegean Sea (Katsanevakis et al., 2007). A monitoring plastic ingestion by *Fulmarus glacialis* was done in the North Sea (van Franeker et al., 2011). There are two models in Pelagos Sanctuary in Mediterranean Sea to predict the plastic accumulation in fin whales (Fossi et al., 2017; Guerrini et al., 2019). Finally, a paper that used linear model to predict the abundance of microplastics in Indonesian Manta Ray and Whale Shark feeding grounds (Germanov et al., 2019).

Finally, there are some papers that do not refer to any of the themes mentioned above. For example, Material Flow Analysis to Household Solid Waste and Marine Litter on a Small Island Developing State (Republic of Palau) was found (Owens et al., 2011). Holmes et al. (2014) study the role of estuaries in modifying the adsorptive properties of new and aged plastics towards trace metals. In the same way, in an estuarine gradient, marine debris' transboundary was studied through hydrodynamic models, ground truthing estimates and regressive vector analysis (Krelling et al., 2017). In 2019, Martins et al. (2019) made predictions of quantity, distribution and plastic pollution effects on marine ecosystems in order to develop in a future a numerical model. Although numeric models and analysis, also help to definition of marine litter clean-up and mitigation strategies at an estuarine scale (Núñez et al., 2019).

4.2. Modelling

Due to the dynamic nature of our system, system dynamics is used for studying and managing such as complex system which change over time, as a method of analysing problems in which time is an important factor (Fishwick, 2007; Ford, 1999). The dynamic problem studied with the model is the accumulation of plastics in the marine environment: once plastics enters to the ocean, they distribute in different media, multimedia dynamic modelling is developed implementing four model's phases increasing gradually the complexity.

A model is a simplified representation of reality that emphasizes those aspects that are considered important and omits all those properties considered non-essential (Silva Gómez et al., 2005). According to Silva Gómez et al. (2005) models can be classify considering different parameters such as time, space, descriptive level or mathematical formulation. Accordingly, models developed in this work are dynamic (the interesting thing is to know the evolution of plastic over time), theoretical (there is knowledge of the physical principles of the system, providing the model with great versatility), deterministic (they are not executed with random variables, involving a complexity of calculation, providing acceptable long-term results), multimedia (representing the movement of plastic between various phases).

The developed model represents the accumulation of plastics in different ocean compartments: surface, water column, seafloor and mobilization of microplastics to biota. Once the model is calibrated and validated, Dynamic Material Flow Analysis (MFA) can be executed running it. MFA is a tool that comes up with focus of system dynamics, and these models provide a method for connecting the material flows into and out of a defined system (Owens et al., 2011). Sensibility analysis is applied to identify the parameters running the system and scenarios are design to be studied using the model.

The selected software is Vensim PLE, available to build flows and stocks diagrams and modelling based on it (Ventana Systems, 2020).

4.2.1. The model

The model consists of four phases. Each phase will incorporate more elements in order to complicate the model. The phases of the model are:

- First phase of the model: it only takes into account the input of both macro and microplastics into the ocean and the degradation from macro to micro. In this phase, the amount of both macro and microplastics in the ocean is obtained.
- Second phase of the model: it incorporates data on the amount of macro and microplastics floating. Therefore, from the second model, the amount of both macro and microplastics that float and both macro and microplastics that sink are obtained (it is assumed that everything that does not float will sink)
- Third phase of the model: it incorporates data from both macro and microplastics that sink and float, assuming everything else stays in the water column. This phase, therefore incorporates one more compartment for both macro and microplastics. Obtaining plastics on the surface, in the water column and on the seabed.
- Fourth phase of the model: it incorporates the ingestion of microplastics by the biomass of fish in the sea. Therefore, this last model incorporates one more compartment to the surface, water column and seabed, which would be the biomass of fish, obtaining amounts of microplastics ingested.

4.2.1.1. Model's phase first. This is the simplest phase of the model, that shows the total worldwide accumulation of plastics (macroplastics and microplastics) in oceans, being both the two existences (accumulation variables) of the model. Three flows are considered: "input of primary macroplastics to the ocean", "input of primary microplastics to the ocean" and "macroplastics fragmentation to microplastics in the ocean". Fig. 4(a) shows the flows and stocks diagram of the first phase developed in Vensim.

This model is based on the annual plastic production. Therefore, historic data on the amount of plastic produced in different years from 1950 to 2020 have been compiled.

Parameter estimation: to calculate the input of plastics into the ocean, a rate of 3 % is applied to annual production. Although this data is estimated for 2010, it is believed that it can be similar for other years (Ritchie and Roser, 2018). According to Sherrington (2016), 12.2 million tonnes of plastic end up in the ocean, of which 0.95 million tonnes are microplastics. From this data the percentage of macroplastics and microplastics can be extrapolate. The 92 % as macroplastics and the 8 % as microplastics.

The macroplastics fragmentation flow to secondary microplastics into the ocean is calculated considering data from polyethylene compounds, one of the most abundant plastic types in the marine environment

(54.6 %), followed by propylene (16.5 %) and polystyrene (9.7 %) (*La* Vanguardia, 2019). Therefore, all plastics present in the ocean are considered as polyethylene in terms of fragmentation. Macroplastic size is assumed as 500 μm (standard size of a water bottle). Fragmentation data for different polymers in the marine environment exist for polyethylene compounds: PET (110 μm / year), HDPE (9.5 μm / year) and LDPE (10 μm/year) (Chamas et al., 2020). Therefore, an average of 43 μm/year is assumed. Knowing that a macroplastic of 500 μm and a fragmentation rate of 43 μm/year have been assumed, it will take 12 years to fragment a macroplastic to microplastic.

The model has been run from 1930 to 2020 (last year with data) with a time step of one year. Initial values for existences in 1930 introduced to the model are zero millions of tons of both macroplastics and microplastics in the ocean. The model runs with a time step of one year considered the fragmentation rate, reason for what introduced historical data are annual.

Fig. 4 (b), (c), (d) show the results of simulation, Fig. 4(b) represents the direct input of total plastics to the ocean (green), the primary microplastics input (red) and the macroplastics input (blue). The total plastics input in the system increases over the time. In 1993 there was a total input of 4.41 million of plastic tonnes and in 2020 this quantity increases until 11 million of tonnes. In the same way, primary microplastics and macroplastics increase. The trend of these last are the same that total plastics. The input of primary microplastics to the ocean is lower than macroplastics, representing a very low percentage of the total. Fig. 4 (c) shows that the flow of macroplastics that fragment into microplastics increases over the years, although the first years are minimal or null. Fig. 4(d) shows that the macroplastics accumulated in the ocean are higher than microplastics until 1990, but in 1991 this trend changes. In 2020 the result obtained is 176.9 million tonnes of microplastics and 117.3 million tonnes of macroplastics. This model evidences that the plastics size varies greatly in the marine environment.

Although the amount of plastic in the ocean is unknown, there are estimations that the amount of microplastics is higher than macroplastics. Yuan et al. (2020) estimate that microplastics account 92 % of plastic waste in the ocean. Although this value is not observed in the model, this follows the same trend in recent years being higher the amount of microplastics.

There are sources (European Parliament, 2018), which state that 69–81 % of microplastics in the ocean correspond to secondary microplastics. This model shows a very low primary microplastics input to the ocean regarding to the accumulated quantity. This is explained by the fact that most of the microplastics are secondary due to fragmentation.

One of the most common and significant tests for model validation is to set the inputs to the model at their historical values and see if the outputs match history. The first phase of the model is in line with estimates found in the literature. Ritchie and Roser (2018) affirm that in 2010, 8 million tonnes of plastic ended up in the Ocean. In addition, Jambeck et al. (2015) estimates that between 4.8 and 12.7 million tonnes of plastic would end up in the sea. This model almost exactly matches data of 2010. Fig. 4(e) shows the approximation to 8 million tons in 2010. In addition, Yick and Travers (2022) state that 243.978 million tonnes of plastic in the ocean have been estimated, and the sum of both the accumulation of macro and microplastics shown by our model is very close to that value. The value of the model is 294.2.

The sensitive parameters of the first phase of the model are: the plastics rate to the sea from production; both micro and macroplastics rates; and macroplastics fragmentation half-life to microplastics in the ocean:

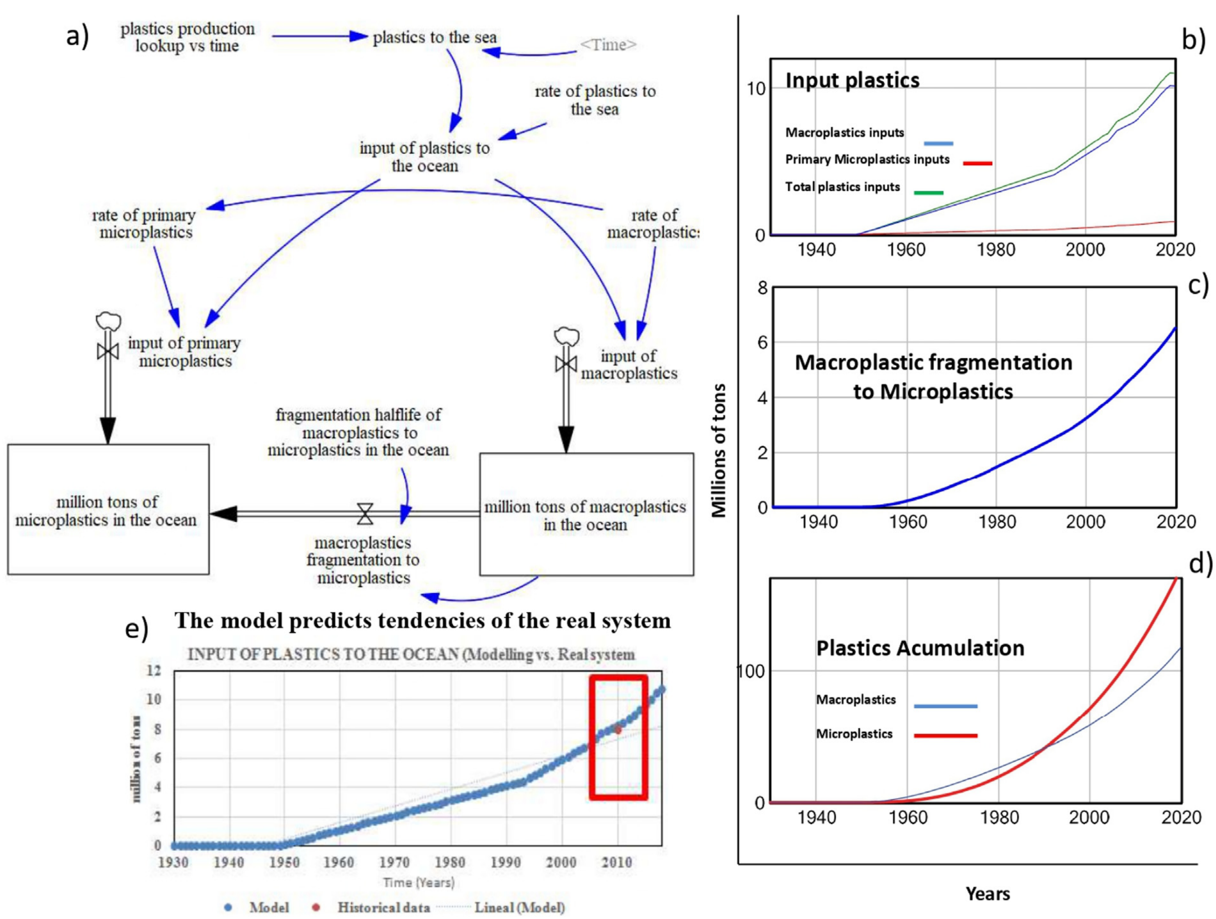

Fig. 4. First simple system dynamics model of mobilization of macroplastics and microplastics in the marine environment developed with Vensim.

- Plastics rate input to the ocean: if this parameter is varied, the other parameters that depend on it will change. For example, if it increases, the micro and macroplastics also increase.
- Macro and Microplastics rate: if macroplastics rate increases, the microplastics rate would decrease, reducing the primary microplastics. The macroplastic rate is very sensitive and increasing it would make an unrealistic model.
- Macroplastics half-life to Microplastics: if the macroplastics half-life before fragmentation increases, the microplastics would not increase as much. Otherwise, if it is reduced, microplastics would increase much faster.

The accumulation of plastics in oceans increases with time because the new plastic input adds to the plastic already accumulated in previous years, and this happens because plastic biodegradation rate is minimal and may take decades to occur.

4.2.1.2. Model's phase second. The second phase of the model aims to visualize in which part of the ocean the plastics will accumulate. Showing how many micro and macroplastics are in both the water column and the ocean surface, being these the four existences of the model. Six flows are considered: “input of primary microplastics”, “input of macroplastics”, “macroplastics from surface to water column”, “microplastics from water column to surface”, “macroplastics fragmentation to microplastics (ocean water column)” and “macroplastics fragmentation to microplastics (ocean surface)” (Fig. 5 (a)).

Parameter estimation: to run this phase, the input data of the first phase of the model are used, knowing that only 1 % of the macroplastics are superficial (Sherrington, 2016), and 0.5 % of the microplastics that input to the water column, float (UNEP and GRID-Arendal, 2016).

Unlike the first phase, it is necessary to consider that the half-life before fragmentation can be different for plastics in the water column or plastics on the surface. Plastics on the surface or floating are affected by solar heat conditions and ultraviolet radiation, whereas those of the water column not so much. To calculate the half-life of the floating plastics before fragmentation, the data defined in the first phase of the model for marine conditions were used by averaging the three PET polymers (PET, HDPE and LDPE). For plastics in the water column, the same was done but, in other conditions of heat and radiation. The same value for both was obtained, 12 years (Chamas et al., 2020).

Primary microplastics reach to the water column is assumed. Their main sources are terrestrial and by wastewater systems that have an output to the water column, as emissaries. To calculate the flow of microplastics from the water column to the surface, the amount of microplastics is multiplied by 0.005 (as described above, the 0.5 % floats). Macroplastics instead, input to the ocean surface directly. To calculate how many of these macroplastics stop floating, the input quantity is multiplied by 0.99 (the 1 % are superficial). Finally, two fragmentation flows from macroplastics to microplastics are calculated (the half-life before fragmentation is the same in both column water and surface, 12 years).

Like the first phase of the model, the second runs from 1930 to 2020. Fig. 5 (b), (c), (d) show the results of simulation, where Fig. 5 (b) shows that the most of plastics are in the water column (red), compared to the few floating plastics (blue). In 2020 there are <10 million tonnes of floating macroplastics, compared to 27.7 million tonnes of floating microplastics.

Fig. 5 (c) shows that the amount of microplastics is higher, as the first phase of the model. In both micro and macroplastics, the difference between floating and non-floating is very noticeable. Fig. 5(d) shows how the formation of secondary microplastics increases over time due to the fragmentation.

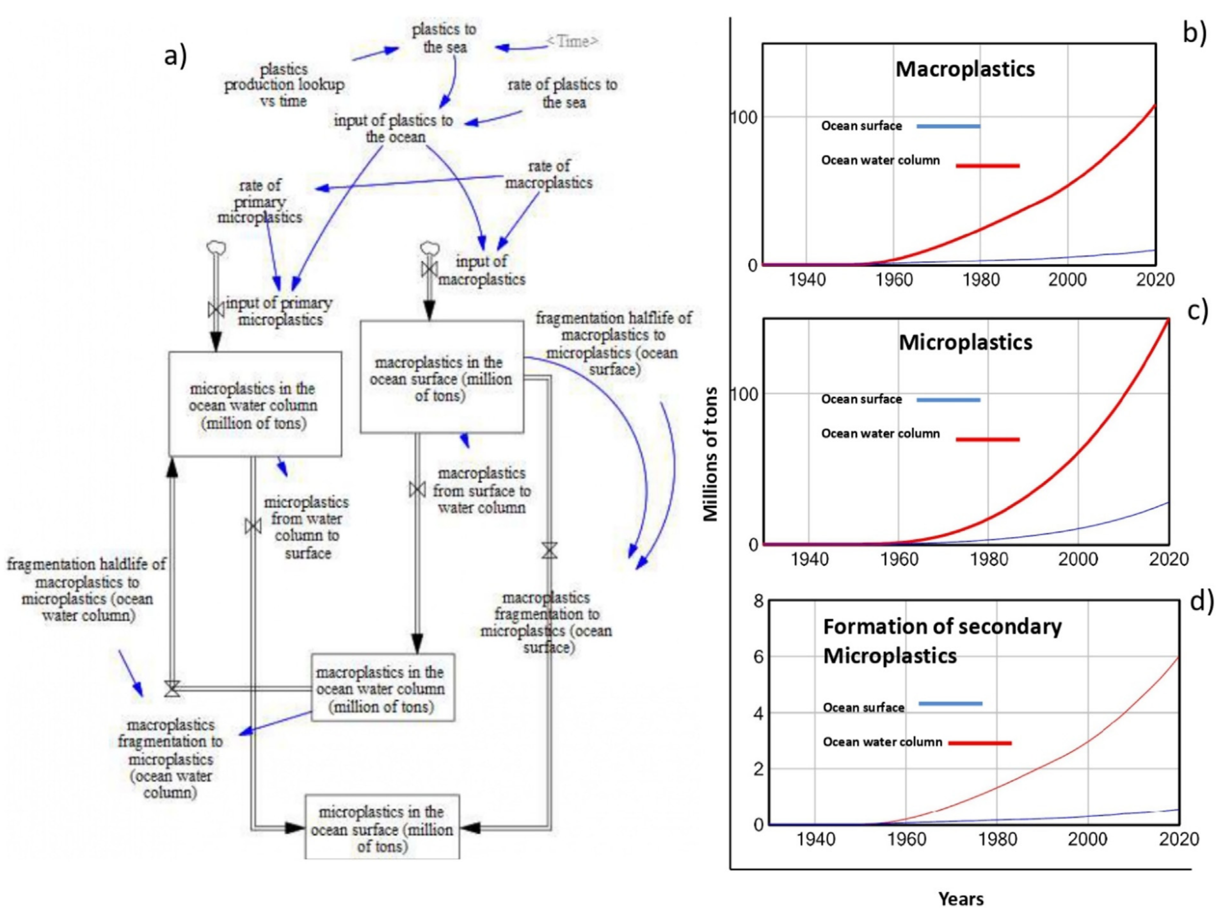

Fig. 5. Second system dynamics model of mobilization of macroplastics and microplastics in the marine environment developed with Vensim.

The results obtained in this phase are expected. Most of the scientific literature claims that the greatest amount of plastic is not found on the surface. Although it is the most studied plastic type, there are very different estimates.

This phase, like the first, is very sensitive: to the half-life before fragmentation, to the rate of plastics and the rate of macroplastics. If a larger size were assumed for macroplastics, there would be fewer microplastics. Also, if a different plastic than PE were assumed, with a different fragmentation rate, the model would vary significantly.

This phase of the model obtains a large amount of floating plastic, compared to bibliographic estimates. This is due to the rate of movement towards the water column or towards the surface since there is not enough data available.

4.2.1.3. Model's phase third. The dynamic problem is amplified for the third phase, where the main objective is to know the amount of plastic that accumulates in the sediments. The accumulation of both, macroplastics and microplastics on three stocks each one (six existences): on the surface (floating plastics), plastics that remain in the water column and plastics that fall to the ocean floor as shown in Fig. 6 (a). Moreover, nine flows are considered: "input of primary microplastics", "microplastics from water column to surface", "microplastics from water column to seafloor", "input of macroplastics", "macroplastics fragmentation to microplastics (ocean water column)", "macroplastics from surface to water column", "macroplastics fragmentation to microplastics (ocean surface)", "macroplastics from surface to the seafloor" and "macroplastics fragmentation to microplastics (seafloor)".

The input data for this phase is the same as for the first and second phases, based on annual plastic production. It is also run for the same period, 1930–2020.

This phase of the model assumes that macroplastics reach the ocean directly to the surface, one part goes towards the water column, and in this case another part will go to the ocean floor. For microplastics, it is assumed that they reach the water column, and one part will move to the surface and another to the bottom.

Fig. 6 (a) shows the third flows and stocks phase. From the stocks of macroplastics, different fragmentation flows are defined towards the stocks of microplastics. In this case, there are three fragmentation flows from macro to microplastics, one on the surface, one in the water column and the last one on the seabed.

Parameter estimation: for these three flows, the same half-life before fragmentation was used as in previous cases (12 years) and the same size of macroplastics as in the two previous cases (500 μm).

In this phase of the model, it is necessary to know that 94 % of the plastics that enter the ocean each year will go to the ocean floor (Sherrington, 2016). Therefore, as we already knew that 0.5 % of microplastics remain on the surface (UNEP and GRID-Arendal, 2016), we can calculate that 5.5 % remain in the water column. The amount of macroplastics that remain on the surface is also known, being 1 % (Sherrington, 2016). Therefore, 5 % macroplastics will remain in the water column.

Figs. 6 (b), (c), (d) show the results of simulation. Fig. 6 (b) shows the amount of macroplastics in each compartment. The green line, which represents the macroplastics on the ocean floor increases considerably over the years. The same occurs in the Fig. 6 (c), which represents the amount of microplastics in each compartment.

Fig. 6 (c) represents the fragmentation of macroplastics to microplastics. The majority of the macroplastics pass to the seabed each year. Because the same fragmentation rate applies to all three parts of the ocean, it is normal for the largest contribution of secondary microplastics to be at the bottom.

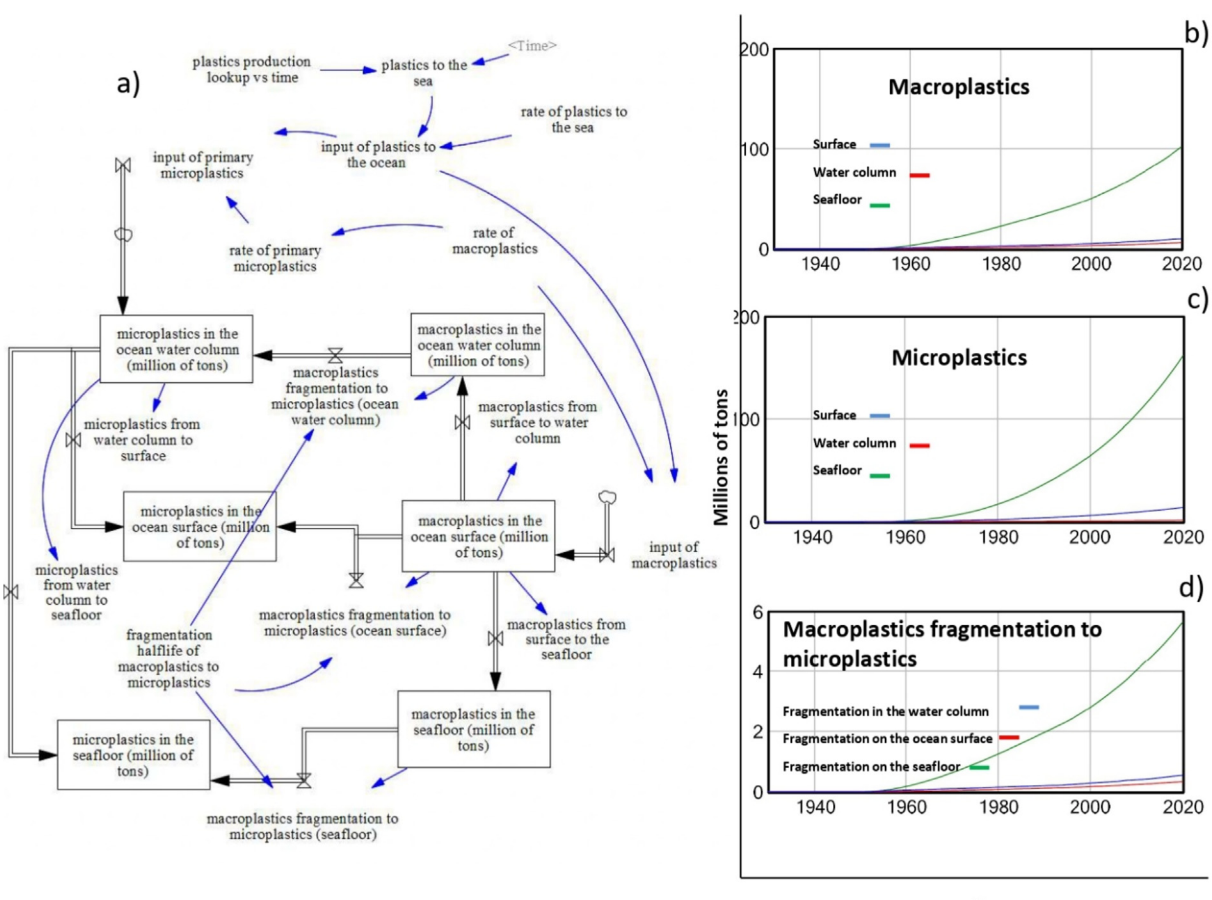

Fig. 6. Third system dynamics model of mobilization of macroplastics and microplastics in the marine environment developed with Vensim.

This phase, like the previous one, is very sensitive to the parameters of half-life before fragmentation, the rate of macroplastics (and microplastics) and the rate of plastics to the sea.

In addition, this phase shows how macroplastics and microplastics are distributed throughout the ocean water column once they reach the environment. Showing theoretical amounts of plastic that can accumulate over the years in marine sediments.

All current estimates say that most marine plastic is not found on the surface, although it is the part of the ocean more studied. Some studies say that plastics in sediments are 94 % of the total (Sherrington, 2016). But there are others that estimate, for example, 70 %, on the European coasts (Galgani et al., 2000). This agrees with the model results.

4.2.1.4. Model's phase fourth. Unlike the previous phases, the fourth phase focuses only on microplastics. Specifically, in the movement of microplastics from the ocean to the biota.

Therefore, the dynamic problem in this case is the accumulation of plastic in the three zones of the ocean (surface, water column and sea bottom), but focusing on microplastics that can potentially be mobilized to marine biota. Therefore, this phase has seven existences that are the same of the third phase adding “microplastics ingested by fishes” Fig. 7 (a).

To create this phase, it is assumed that most of the microplastics that move to the biota are those that are in the water column. It is also assumed that all biota are fish.

Parameter estimation: data collected for this phase is the same as for the third phase. The new flow “microplastics in biota” is calculated based on the average amount of microplastics ingested by fish. Boerger et al. (2010) estimate an average intake of 1.57 mg of plastic per fish, in addition, based on this work, the amount of microplastics per ton of fish in the sea can be estimated, obtaining a value of 0.6 kg of microplastics per ton of fish.

For this phase it is necessary to know the biomass of fish in the ocean, this data is observed in several works that can estimate it, obtaining an average of 1.5 mil millions of tonnes of fish in the sea (Tremblay-Boyer et al., 2011; Wilson et al., 2009; Jennings et al., 2008).

The fourth phase model runs just like the previous ones between 1930 and 2020. Once run, simulation results in the microplastics stocks on the surface and sediments and for the macroplastics are as expected. The difference in this phase is centred on the microplastics in the water column (microplastics ingested by fish).

As microplastics increase in the ocean over time, their ingestion by fish also increases (Fig. 7 (b,c)). Microplastics show an upward trend over time into the future. The amount of microplastics in biota in a real-world scenario is thought to be lower, due to removal through fishing or other activities. Still, fish can capture a worrying amount of microplastics through ingestion. Fig. 7 (b,c) shows the tendency of microplastics to increase, despite the flow to marine biota.

Like previous phases, this one is sensitive to the half-life before fragmentation, the rate of macroplastics and microplastics and the rate of plastics in the sea. In addition to these sensitive points, the quantity of fish in the ocean is added. If this amount increases, the amount of intake will be higher.

As a result, this phase shows that in 1952 there was already a movement of microplastics to fish. Instead, the quantity began to increase and, in 2020 there are >7000 t of microplastics accumulated in fish. Although there are studies in local areas, like Carson (2013), which estimates that fish ingest 1.3 t of microplastics per year in an area of 15 km^2, models for the amounts

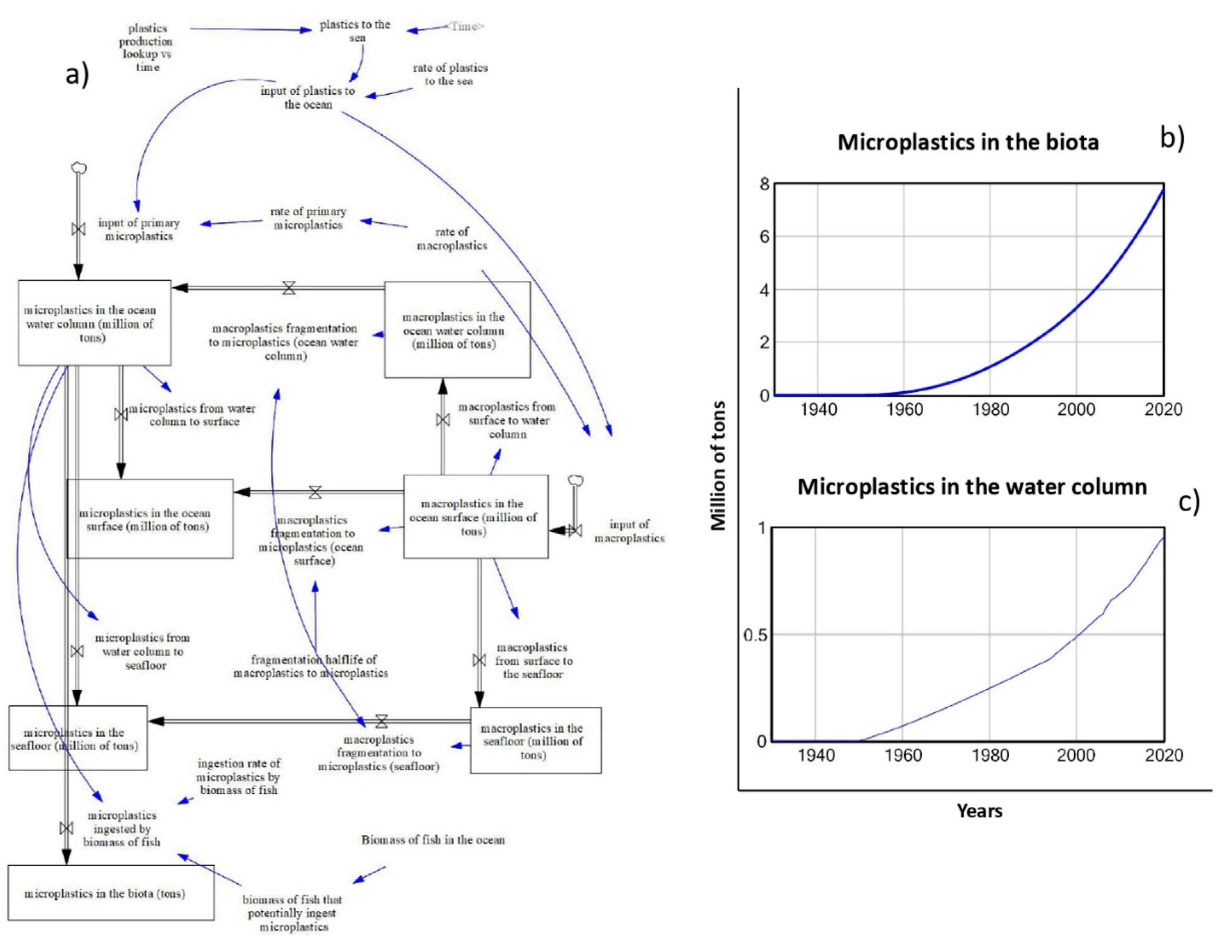

Fig. 7. Fourth system dynamics model of mobilization of macroplastics and microplastics in the marine environment developed with Vensim.

of microplastics ingested worldwide have not been found. Therefore, to compare the result of this model with historical results to date is very difficult.

5. Results and discussion

978 articles have been reviewed and analysed to study the origin, sources and sinks of plastic. Estimates of the amount of plastic in the sea are very different depending on the media consulted. According to the collected articles, the sources can be classified into terrestrial and oceanic sources. It is considered that 80 % (Sherrington, 2016) of the inputs are from land sources compared to 20 % of the oceanic inputs.

On the other hand, the plastics more abundant are the classified by Parker (2018) as Others (O), LDPE and PP. Theses plastics are not biodegradable and can accumulate in five compartments: surface, water column, seabed, littoral and in biota. Most of the studies reviewed correspond to floating plastics found on the ocean surface. Although the ocean surface is the most studied, the compartment with the highest concentration of plastic, with 94 % is the seabed (Sherrington, 2016).

Regarding the transformation of plastic in the marine environment, it follows that the marine environment is not a means of disposal, although it undergoes transformations, it tends to accumulate.

After reviewing the 978 papers, a classification grouped by themes is obtained (Fig. 2). The more repeated topic was “macroplastics/mesoplastics”. Although the topic “Microplastic/nanoplastics” is less represented it is very current. From all studies that deal microplásticos, 36 % of these were made in two last years.

Management strategies are represented in 15 % of the articles reviewed. These are related to plastic management strategies to reduce its impact or legislation. This is a very current topic, the 33 % of studies were found in two last years. For this reason, there is no notification of many strategies to manipulate plastic in the oceans. The more important projects are Clean Atlantic (Interreg Atlantic Area, 2020) and Ocean Cleanup (The ocean clean up, 2021). On the other hand, citizen science campaigns such as the Spanish project “Libera, unidos contra la naturaleza” (Proyecto Libera, 2020).

It was found that 267 of papers reviewed represent the topic “monitoring and modelling”. This topic has an upward trend in terms of number of studies in recent years. In the two last the articles reviewed were the 51 %. Nowadays there are models of the spatial distribution focused on local areas as Mediterranean Sea (Manusi et al., 2020).

After the reviewing, four model's phases have been built from the simplest to the most complex that represent the mobilizations of the plastic between the oceanic compartments.

Using plastic production data and fragmentation rates, from the simplest to the most complex model's phases were run. More data have been added to increase the complexity of the phases of the model. For the simplest phase only the accumulation of macroplastics and microplastics is considered. Then the oceanic compartments are gradually included for both macroplastics and microplastics. The compartments are floating plastics, plastics in the water column and plastics on the seabed. The last phase of the model, and the more complex uses data from the previous phases. In addition, a new compartment is included, the biota, only considering the accumulation of microplastics. Main results found by model's phases are:

- Model's phase 1: High input flow and greats accumulations of microplastics and macroplastics
- Model's phase 2: Floating plastics are the least abundant
- Model's phase 3: Seafloor is a great plastic sink, especially microplastics
- Model's phase 4: Great number of plastics are moved to the biota

Studying data from the bibliography it is observed that this model is very close to a real system. Similarities have been observed in this model, such as the 8 million tons that ended up in the ocean in 2010 (Ritchie and Roser, 2018). Most of the marine plastic accumulates in seabed, but there are not currently many sources handling this data globally, although all scientific sources say that this percentage is very high in the local areas sampled (Sherrington, 2016). There are several works that show that there are more microplastics than macroplastics in sediments, or at least in the local areas where the samples were collected. For example, a study of plastic litter in sediments in the Telascia Bay Nature Park (Croatia) says that 88.71 % of the plastics sampled are microplastics (Blaskovic et al., 2017). Another study in an archipelago in the Tyrrhenian Sea states that 94.3 % of the plastic represents microplastics (Fastelli et al., 2016).

Regarding the model's phase fourth, it is observed that the transfer of microplastics to the biota is increasing. Microplastic particles have been found worldwide in marine animals (Covernton et al., 2021), this may be due to the increase of microplastics in the water column. Although this phase of model is not easy to compare with a real system, since currently the knowledge of the trophic transfer of microplastics is still scarce (Hasegawa and Nakaoka, 2021). This last phase of the model adapts previous data by adding new information, thus, it is the closest phase to the real system.

6. Conclusions

This document expands the current knowledge about plastic as a pollutant in the marine environment and offers a broad overview of plastic pollution in the sea. It reviews the problem of marine plastics and develops a dynamic MFA by preliminary models on the mobilization and accumulation of plastics in the marine environment.

First, a bibliographic search was carried out and it was classified into seven categories according to the most important topics found. From this review, a research work that analyses current management strategies is obtained. Most of the papers are about management measures on land to prevent the plastic's arrival in the marine environment. The citizen campaigns for the elimination of plastics and various national and international projects stand out among other strategies. Although these are fundamental to face the problem of plastics, few studies or strategies have been found. Improving the knowledge about the methodologies and techniques for studying micro/nanoplastics will help to define better strategies.

In addition, the review provides knowledge of the main sources and sinks of plastic into the ocean. Therefore, it is collected that the land source represents 80 % of the plastic inputs to the sea and the seabed, which is a large sink (most of the plastic waste in the marine environment is settled to the bottom of the seafloor). Information is obtained on the transformations that plastics undergo in the sea (degradation and fragmentation) even though the marine environment is not a means of disposal, but of accumulation.

This work has demonstrated the usefulness of the model to study dynamic problems. The dynamic problem studied with the model is the accumulation of plastics in the marine environment: once plastics enters to the ocean, they distribute in different media. Four phases of a dynamic model that represent the mobilization of plastic in the ocean are developed, progressively increasing the complexity.

The model shows that plastic debris in the form of macroplastics, microplastics and secondary microplastics in the ocean continues to increase over the years, mostly in the water column. Most of it ends up being accumulated on the sea floor, but the plastic's increase in the water column causes at the same time the increase of plastic in living beings, also affecting humans.

The developed model describes well the real system trends in the different media. The model is sensitive to parameters that can be modified to consider other possible scenarios: plastics index entry into the ocean, macro and microplastics rate, the half-life of macroplastics to microplastics and the number of fish in the ocean. Adapting and adjusting the model can predict future trends in plastics. Being modelling a useful tool to support new regulations and strategies to deal with the problem of plastic waste. This work has expanded knowledge about the real problem of marine plastic debris pollution around the world.

CRediT authorship contribution statement

Adriana García Rellán: original draft preparation, investigation, data curation, conceptualization, analysis, writing-reviewing and editing, methodology, software. **Diego Vázquez Ares**: original draft preparation, investigation, data curation, software. **Constantino Vázquez Brea**: original draft preparation, conceptualization, analysis, writing-reviewing and editing. **Ahinara Francisco López**: writing-reviewing and editing, software. **Pastora M. Bello Bugallo**: supervision, conceptualization, original draft preparation, investigation, analysis, methodology, writing-reviewing and editing, software.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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