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Artículo de Revisión

Contaminación de océanos por plásticos: técnicas de cuantificación y remoción

Ocean pollution by plastics: quantification and removal techniques

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Resumen

Los plásticos provocan daños internos o externos a las especies marinas y problemas de salud pública. Además, contribuyen al deterioro del sistema acuático ya que transportan otros contaminantes como disruptores endocrinos, retardantes de llama, entre otros. Esta investigación propone una revisión sistemática de la literatura de los últimos 5 años para examinar los métodos de biorremediación propuestos para la contaminación plástica. Los métodos degradativos (microorganismos, hongos y algas) representan el 45% de los artículos utilizados en la revisión sistemática. Otros métodos de remediación directa identificados son los procesos oxidativos avanzados (17%) y los procesos endotérmicos (14%). Si bien existen métodos aplicables como la pirólisis y la termodegradación, tienen desventajas como el costo energético, la baja calidad del producto y el riesgo de liberar microplásticos al medio ambiente. El escalamiento entre las dimensiones del laboratorio y las necesidades reales constituyen desafíos para las futuras aplicaciones de estos métodos.

Palabras clave: Remediación; plástico; océano; contaminación, degradación.
Código UNESCO: 2304.16 - Análisis de Polímeros.

Abstract

Plastics negatively cause internal or external damage to marine species and public health problems. In addition, they contribute to the deterioration of the aquatic system since they transport other pollutants such as endocrine disruptors, and flame retardants, among others. This research proposes a systematic review of the literature from the last 5 years to examine the bioremediation methods proposed for plastic pollution. Degradative methods (microorganisms, fungi, and algae) represent 45% of the articles used in the systematic review. Other direct remediation methods identified are advanced oxidative processes (17%) and endothermic processes (14%). Although there are applicable methods such as pyrolysis and thermodegradation, they have disadvantages such as energy cost, low product quality, and the risk of releasing microplastics into the environment. The scaling between the dimensions of the laboratory and the real needs constitutes challenges for the future applications of these methods.

Keywords: Remediation; plastic; ocean; pollution; degradation.
UNESCO Code: 2304.16 - Polymer analysis

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1. Introduction

Plastic pollution has become a problem in recent times. Plastics are classified as relatively new materials worldwide since their existence does not exceed more than a century. The first plastic known at the beginning of the 20th century was Bakelite, but it was not until the end of World War II that it began to be manufactured on a massive scale [1]. Plastics are synthetic or semi-synthetic organic polymers, easily molded with heat and pressure. The production of plastics has promoted several high-level technological advances and due to their versatility, they are used in the food, health and medicine, construction, and automotive industries, among others [2].

Plastic products or materials consist of a polymeric structure such as polyethylene, vinyl chloride, polystyrene, polypropylene, among others, and monomers joined together to form a chemical additive. The performance and appearance of plastics increases with the incorporation of additives such as fillers, plasticizers, flame retardants, heat stabilizers, antimicrobial agents, and colorants [1]. This material, although it seems harmless, usually contains and releases toxic substances such as bisphenol A or phthalates, which are persistent and easily dispersed in the environment. Additionally, it is a material that is not recycled or reused on a large scale, since it is still cheaper to manufacture plastics from virgin raw materials [3].

The inappropriate disposal of this material, as well as its long degradation time, promotes its presence in the world's oceans. The five areas with the highest concentration of plastics are in the Indian Ocean, the Atlantic Ocean (north and south) and the Pacific Ocean (north and south) [4], [5]. It is estimated that 0.1% of the world's annual plastic production in all size classes constitutes plastic pollution on the sea surface [6]. These materials enter the marine environment through fishing boats, activities related to tourists, industrial discharges, and landfills near the coastline. In the marine environment, plastics lose firmness and fragment over time due to physicochemical processes such as exposure to sunlight, oxidation, or the physical action of waves and ocean currents. This physical fragmentation is not considered a degradation. In many cases is only a size reduction without changes in the chemical configuration acquired in its manufacture [7].

The degradation of these plastics can generate low molecular weight polymers, as monomers and oligomers in many cases, as well as new terminal groups. For its part, the fragmentation of plastics generates microplastics (MPs) and nanoplastics (NPs), which are particles of less than 5 mm and with dimensions between 1 and 100 nm, respectively. Most of the microplastics identified in the oceans are: high-density polyethylene (PE-HPDE), polyethylene terephthalate (PET), polypropylene (PP) and polystyrene (PS). To a lesser extent, traces of nylon, polyurethane (PUR), ethyl vinyl acetate (EVA), polyvinyl chloride (PVC) have been detected [8], [9].

Plastics can act as a vector that transports other pollutants, altering environmental fate and its effects. These can transfer adsorbed contaminants from the surrounding water, such as endocrine disruptors and persistent organic pollutants. The release of auxiliary chemicals and additives from plastics could provide an important pathway for the transfer of chemicals to and thus affect biota [1], [10]. The micro and nanoplastics produced threaten marine fauna, including plankton, crustaceans, and fish, as they can cause internal or external injuries, movement and growth limitation of organisms, and death. These materials could cause health problems such as chromosomal alterations, obesity, cancer, and infertility [5], [11]. This research proposes a systematic literature review to examine microplastic remediation methods and identify knowledge gaps for future research.

2. Development

2.1. Materials and methods

The review included articles published in scientific journals indexed in Scopus, between 2018-2023, under the search terms "plastics AND ocean AND pollution AND remediation". The methodology used was the

PRISMA model [12]. This methodology proposes to start with a preliminary search, exclude articles that do not meet the search criteria, and then classify them according to direct and indirect methods. Direct methods (MD) propose articles that promote plastic removal techniques aimed at procedures and technologies focused on their study and advancement. Indirect methods (MI) manage the prevention of plastic pollution in the seas, prioritizing the treatment of water that could generate indirect pollution in the oceans.

Under the established search criteria, we collected a total of 678 articles. A first debugging eliminated duplicate documents and publications unrelated to the subject of this review, resulting in a selection of 135 articles. Subsequently, in a second review, this number was reduced to 112, by eliminating those that addressed, for example, processes for removing plastic contaminants from the soil. Finally, 51 articles were selected, which address the issue of elimination of plastics present in the seas. These were categorized into MD and MI (Figure 1). These articles explored multiple methods of plastic removal, based on their own experiences.

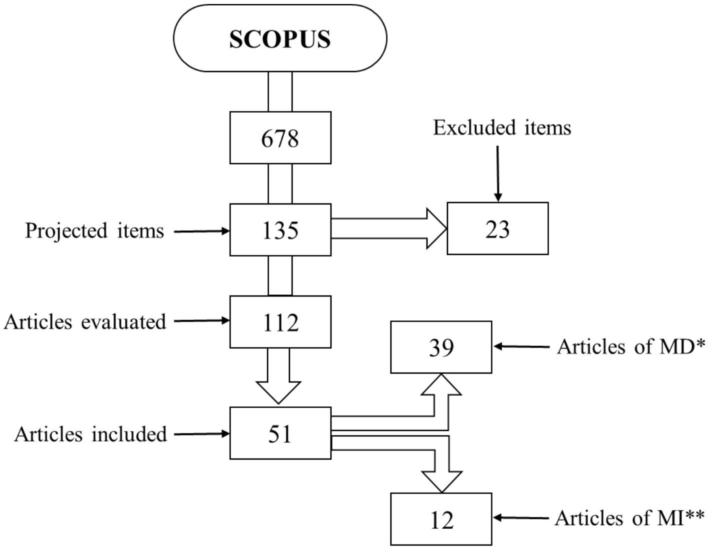

Figure 1. Flowchart of the articles included in the review. *Direct methods. **Indirect methods.

More than half of the articles included in the research were bibliographic reviews focused mainly on the description of remediation methods. The rest were experimental works, where the application of plastic removal methods to specific cases was evaluated (Figure 2).

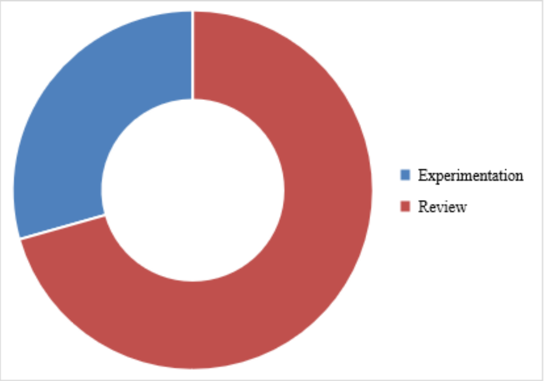

Figure 2. Review articles vs. experimental.

2.2. State of the art of research on plastics and microplastics

The impact of plastic on marine ecosystems is one of the many consequences of anthropogenic activities. Globally, of the 8.3 billion tons (Mt) generated, only 9% and 12% are recycled and incinerated, respectively. The rest ends up in landfills or natural environments, such as the oceans (Table 1) [13]. The current generation rate of plastics assumes a scenario for the year 2050 in which there are more plastics than fish in aquatic ecosystems [14].

Table 1. Plastic pollution in oceans

Ocean	Approximate amount of plastic	Plastic found/area ratio	Plastic type	Observation	Source
Pacific	79000 t	146 - 26898 items/km^2 11879 articles/km^2	PVC, PET, PE, PP, PS, LDPE, NY, HDPE.	Area of 1.6 million km^2 North Pacific and South Pacific gyre. Huawei to Rosario. South Pacific (Chile).	[15] - [17]
Atlantic	765 - 2969 t	329541 particles/km^2	Mixture of microplastics, pellets, fishing lines, fragments, films.	Mediterranean coastal zone (Cullera, Tavernes, Xeraco, Serpis, Piles, Oliva Nova, Deveses, Punta Molins, Denia). Shallow basin of the Mediterranean Sea.	[16], [18]
Antarctic	ND	0.17-0.33 particles/m^2 3524-755 particles/km^2	PES, PE, PU, PET, PE, PP, NY, fishing nets.	Collins Glacier. Collins Bay.	[19], [20]
Artic	26 kg/m^2	202 - 279 particles/km^2	PS, PE, PP, NY, PMMMA, PET.	Ice cores (50 to 100 cm^3 samples). Greenland sea.	[21], [22]
Indico	0.6 Mt/year	0.92 particles/km^2 45 - 200 particles/kg sediment	PET, PVC, HDPE, LDPE. PC, PP, PE, PS.	India. Bay of Bengal. Mumbai, Tuticorin, Dhanushkodi.	[23] - [25]

ND: Not determined. PP: Polypropylene; PE: Polyethylene; LDPE: Low Density Polyethylene; PA: Nylon polyamide; ABS: Acrylonitrile butadiene styrene; PES: Polyethersulfone; PVC: Polyvinyl chloride; PET: Polyethylene terephthalate; PU: Polyurethane; PS: Polystyrene; HDPE: High-density polyethylene; PC: Polycarbonate; RY: Rayon; PTFE: Polytetrafluoroethylene; PMMA: Polymethylmethacrylate.

Plastic pollution directly attacks the aquatic ecosystem, causing alterations in marine flora and fauna [26]. Some pathogenic bacteria create covers on the surfaces of plastics, which can release toxic plasticizers, harmful to organisms that maintain contact with them [27]. The PMs can affect the organisms and the marine sediment, generating vital decay in the system. These particles can easily reach marine life and enter the food chain of species such as plankton, crustaceans and fish [28], [29]. For their part, NPs interfere with the photosynthesis of blood cells, which is why they are considered more dangerous particles than microplastics, due to their ease of penetration into biological membranes [30].

Plastic pollution in marine aquatic systems is directly related to human activities [31]. Industrial and domestic wastewater release plastics, in different sizes and structures [32]. These enter the oceans directly or indirectly as the water systems are interconnected. In this context, estimates suggest that the seabed could contain 35 times more PM than the surface and an amount of 4.4 Mt in marine sediments. Calculations establish that rivers transport between 1.15 and 2.41 Mt of polymers to the oceans [33].

Despite the numerous studies on issues related to plastics, this area still demands in-depth exploration in terms of proposing effective methods for their identification, quantification, and prevention and remediation of environmental contamination by these materials [34]. According to the literature reviewed, the years 2021 and 2022 coincide in the number of qualified studies in the database. However, at the beginning of the first quarter of 2023, the number of research articles increased compared to the period corresponding to the previous year. Therefore, the scientific production at the end of 2023 should be higher (Figure 3).

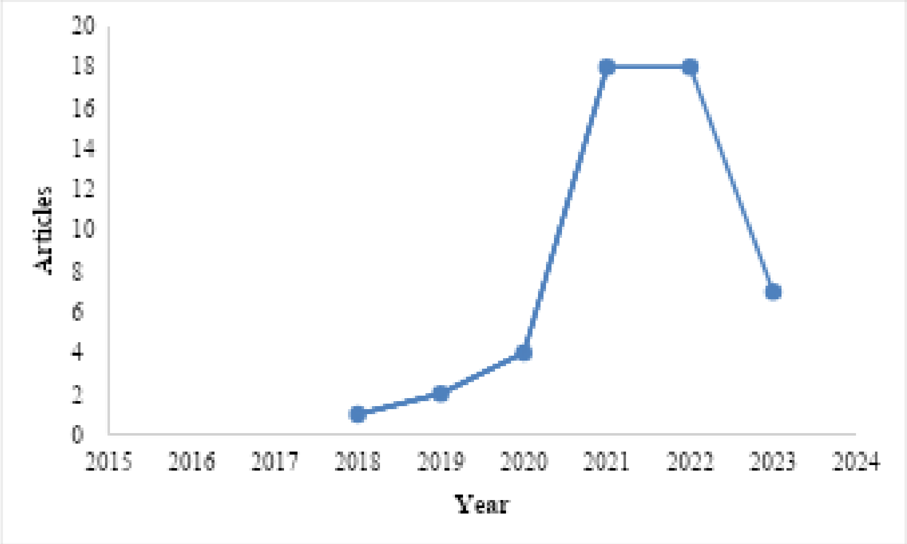

Figure 3. Annual scientific production of articles related to the subject.

The journal Science of the total environment leads the research consulted, corresponding to the period 2018 - 2023, with a favorable rate of increase compared to sources such as Chemosphere and Journal of hazardous materials. Publication sources such as Current opinion in environmental science & health and Journal of environmental chemical engineering maintain the same number of publications over time. However, the journals Green analytical chemistry and Journal of environment management stand out for their low rate of publications, compared to the rest of the journals (Figure 4).

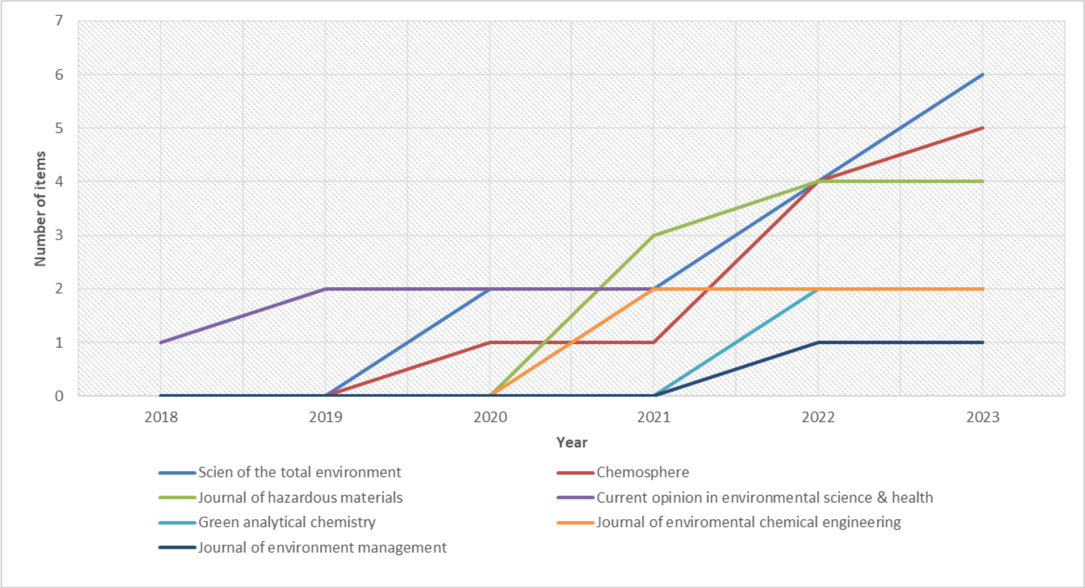

Figure 4. Scientific production related to plastics in oceans between 2018 – 2023.

2.3. Plastic identification methods

The investigations inherent to plastic pollution in oceans address the methods of identification, quantification, and removal of particles. Selection of the removal method requires identification of the polymers. Chromatography (of gases or liquids associated with different detectors such as ultraviolet light or mass spectrophotometry) is a technique with various applications for plastics contaminants determination [35]. The thermodegradation of the polymers precedes the conversion of macromolecules into low molecular weight polymers, allowing the action of chromatography as recognition analysis. Authors [36], [37], [38] use gas chromatography-pyrolysis-mass spectrometry (Py-GC-MS), gas chromatography-thermal desorption-mass spectrometry (TED-GC-MS), liquid chromatography (LC) and gel permeation chromatography (GPC), in the identification of plastic particles.

The recognition of plastic particles mainly uses Fourier (FTIR) and Raman spectrophotometry [36]. Chromatography applied to pyrolysis and thermal desorption techniques are also viable for recognizing plastic particles. The Py-GC-MS technique allows the identification of the chemical compounds formed by the pyrolytic process, with the drawback of not providing information on the size and morphology of the analyzed polymers. However, gel permeation chromatography provides information on the identification of the polymer and its physicochemical properties. In the analysis of complex samples, TED-GC-MS is considered a promising technique [38].

2.4. Remediation methods

2.4.1. Bioremediation

It is necessary to know the degradation process of the plastics present in marine ecosystems. Depending on the environmental environment and the conditions to which the plastics are exposed, they begin to break down. The fragmentations show rates from 1% to 5% and are attributed due to photo-oxidation, thermal degradation and mechanical stress [39].

Once the polymers are broken down into smaller particles, aquatic microorganisms can intervene to break down the particles. Living organisms manage to metabolize plastics and use them as a source of energy and carbon, transfiguring the polymers into H_2O, CO_2, CH_4 y N_2 [40]. Microorganisms such as bacteria and fungi produce enzymes capable of degrading polymers, configuring the stage corresponding to the mineralization caused by enzymatic degradation, concluding in the mentioned final products [41].

There are living organisms that play a degradative role in polymers as an alternative to their reduction, contributing to reduce the environmental impact they cause (Table 2). Although microparticle degradation via microorganisms is a promising approach, it involves a slow process, incomplete mineralization, and unexplored reaction mechanisms. In this sense, it is considered a technology in its initial stage, but with alleged investigations and modifications, it can become a great ally in plastic decontamination [42], [43].

Bacteria, fungi, and algae are biological factors that degrade plastic naturally [44]. Microbial communities that colonize plastic have been characterized in several ocean regions and are distinct from the communities in surrounding waters, which, when isolated from some microorganisms, degrade plastic from other environments. Bacteria such as Erythrobacteraceae and Rhodobacteraceae (Alphaproteobacteria), Flavobacteriaceae (Bacteriodetes), and the phylum of cyanobacteria (such as the genus Phormidium) could play a role in the colonization and possible degradation of plastic in the oceans due to their appearance in marine plastic debris [45]. Marine fungi, like terrestrial and lacustrine fungal taxa, can metabolize recalcitrant compounds, pollutants, and some types of plastic [46]. Among the fungi that degrade plastic are the fungal phyla Ascomycota (Dothideomycetes, Eurotiomycetes, Leotiomycetes, Saccharomycetes and Sordariomycetes), Basidiomycota (Agaricomycetes, Microbotryomycetes, Tremellomycetes, Tritirachiomycetes and Ustilaginomy-cetes) and Mucoromycota (Mucoromycetes) [47].

Algae are diverse organisms that occur in a variety of shapes and sizes in marine ecosystems. Algae grow rapidly, are non-toxic, readily available in nature, and comparatively easy to isolate and colonize plastic surfaces using polymeric carbon. Biodegradation using this group of organisms likely includes carbon mitigation and bioprospecting for value-added products. Plastic surfaces can be biodegradable or protect the polymers from UV radiation and photocatalysis, depending on the type present on the plastic surface [48], [49]. Some studies on the degradative role of these biological factors in polymers as an alternative to their reduction are present in Table 2.

The degradation process depends on factors such as density or functional groups present in the material. Enzymes released by living organisms can transform complex molecules into simple polymers, making plastic particles improve their hydrophilic characteristics [66], [69]. The molecular weight of plastics has a direct effect on the biodegradation process. The higher the molecular weight of the polymer, the lower its degradative potential. Biodegradation with bacteria and fungi is a process that produces a decrease in the molecular weight of plastic contaminants. Even so, techniques that improve the degradation process, such as including synthetic microbial consortia, systems biology tools, and genetic engineering techniques, have been implemented as a complement to obtain a future optimal method, which contributes to reducing the pollutant [56].

In this context, the formation of biofilms is attributed to the accumulation of microorganisms on the surface of polymers in an aquatic environment. Microbial biofilm technology is growing as it enables advances in the biodegradation of polymers, with trap and release actions [51], [58], [73].

Genetic engineering has evolved with the application of modified microorganisms to improve biodegradation potential [74]. Synthetic microbial consortia are part of the genetic evolution, attributing bioremediation of plastics with greater efficiency, creating possibilities to modify microorganisms with genes for specific functions that work together to generate biodegradation in a simple, fast, and optimal way [56]. On the other hand, microbial applications that generate high efficiency without contributing high costs continue to be studied. The application of hyperthermophilic composting suggests advantages in the production of large microbial quantities and in the degradative performance of microplastics, contributing to the scaling of remediation processes since it has a shorter composting period and greater maturity of the process [68].

Microorganisms are a great source of research, although they are not the only method used to reduce environmental pollution attributed to plastics. There are remediation methods as an alternative solution to this problem. Conversion methods, for example, seek to revalue plastics and reduce the environmental impact they cause [75].

2.4.2. Advanced oxidative processes, endothermic and indirect methods

Advanced oxidation processes (AOP), are made up of photodegradation techniques and others similar to Fenton. There are also endothermic methods focused on the conversion of polymers, as well as indirect methods that address the subtraction of polymers as remediation methods for the problem of plastic pollution in marine ecosystems.

Advanced oxidation processes present different adaptations in the studies consulted. Photocatalysis leads to the aging of polymers and photooxidative reactions to cause mineralization (H_2O and CO_2) of the plastic contaminant. The use of catalysts with semiconductor functions has been highlighted [62], [76]. The most common semiconductors include TiO_2 and ZnO in photocatalysis in aqueous media. ZnO has been shown to have a higher discoloration rate compared to its counterpart, a process attributed to the interaction of polymers and oxidative radicals [54], [59].

Table 2. Plastic removal methods by bacteria, fungi and algae in experimental lab scale and real scale

Degradation agent	**Number of articles**	**Techniques used**	**Microbial strain**	**Analyzed plastic**	**Results obtained**	**Reference**
Microbial	21	Pure bacterial cultures, consortia of bacterial cultures, biofilms, hyperthermophilic composting (hTC)	*Rhodococcus sp., rhodococcus rubber, staphylococcus sp., staphylococcus aureus y streptococcus pyogenes, bacillus sp., bacillus cereus, bacillus gottheilii, bacillus subtilis, pseudomonas aeruginosa, pseudomonas putida, pseudomonas chlororaphis, enterobacter asburiae, chelatococcus, lysinibacillus fusiformis, aspergillus niger mellonella, brevibacillus borstelensis, thermomonospora fusca, alcaligenes faecalis, clostridium sp., gusano de cera, polilla de Cera G.*	PP, PE, PET, PS, LDPE, HDPE	The existence of some 130 species capable of degrading plastic particles is reported. It has been verified from a 4% to a 75% decrease in molecular weight of the PM according to the microbial technique used), in experimentation times ranging from 0 to 3 months. In order to improve the efficiency of microbes, there has been an incursion into genetic modification and combined techniques to use an accelerated degradation process.	[30], [50], [51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69]
Fungi	8	Consortia	*Phanerochaete chrysosporium, cladosporium cladosporoides, pycnoporus cinnabarinusand, penicillium simplicissimum, penicillium pinophilum, xephalosporium sp., aspergillus terreus, aspergillus sydowii, aspergillus nonius, aspergillus niger, aspergillus flavus, aspergillus oryzae, trichoderma viride.*	PE, PUR, HDPE, PET, PP, PA, PVC, LDPE	The use of fungi in the degradation of plastics has been reported, with efficiency of up to 15%. Mixed consortia have been used in conjunction with bacteria to improve said value. The disadvantage is the incubation time of the fungi, which determines the efficiency of degradation. Although it is a process that can take three months, studies have been found where degradation reached 20 months.	[50], [54], [56], [65], [66], [70], [71]
Algae	3	Phytoremediation	Marine microalgae: *Ulva prolifera y Fucus vesiculosus* Microalgas de agua dulce: *Microcystispanniformis.* *Scenedesmus sp.* *Hydrocotyle vulgaris*	PE, PP, PS	The study of green species and the available information is limited. Despite this, they are considered an ally in the degradation process through organisms. Although no details have been explored in the field, the environmental and economic gains this process can generate by being called eco-friendly highlighted.	[49], [72], [73]

PET: Polyethylene terephthalate; PP: Polypropylene; PE: Polyethylene; PS: Polystyrene; PVC: Polyvinyl chloride; PUR: Polyurethane; PA: Nylon polyamide; HDPE: High density polyethylene; LDPE: Low density polyethylene.

The traditional Fenton process contemplates the production of reactive hydroxyl radicals when H_2O_2 reacts in the presence o Fe^{2+}. The Fenton process is accelerated with the incorporation of UV-Vis radiation. Another application of this process is the heterogeneous Fenton, which uses solid catalysts that include components that replace ferrous ions, being one more alternative [61]. AOPs are widely studied and applied in the decomposition of different refractory pollutants in the environment, including microplastics in bodies of water. Homogeneous and heterogeneous AOPs, including UV photolysis, UV/H_2O_2, O_3, UV/visible light-induced photocatalysis, and heat and plasma activated peroxymonosulfate, could effectively decompose various types of MPs with different sizes. Although their large-scale application is far from being implemented, it is important to develop reliable technologies to eliminate these emerging pollutants from the environment [77].

Advanced oxidation processes can vary their efficiency according to the reaction conditions (pH, temperature, reaction time, UV radiation, shape of the polluting particle, and reaction medium). The applications of heterogeneous Photo-Fenton and photocatalysis are the methods with the best results exposed in different works, with heterogeneous photocatalysis being the most studied POA in all the adaptations formulated. The research progress that arises in the applications of the Fenton process has promoted the incorporation of electrons as the principal reactant, being called Electro-Fenton, using TiO_2/graphite (TiO_2/C) as a catalyst during the process [76], [78].

Other processes applied as conversion methods linked to finishing the life cycle of plastics are thermal. The increase in energy demand has forced the search for processes that allow sustaining the population without generating environmental damage [79]. The unparalleled increase in plastic makes it consider its use as a raw material in transformation processes as an alternative to reduce pollution, together with the benefit that its application in conversion processes entails energetically. The heat treatment is based on energy recovery since plastics have a high calorific value and daily increase in production [54]. Pyrolysis and gasification are thermal processes with different applications, capable of replacing non-renewable processes and safeguarding the combustion of fossil fuels [60], [80].

Pyrolysis is considered the most reliable technique regarding polymer weight loss in combination with temperature. However, the technique suggests high energy requirements and low product quality. To increase the yield in the process and minimize emissions, catalysts, and closed reactors are used [12], [79]. The pyrolytic method is not the only one studied in plastic particle conversion. The thermodegradation independent of natural environmental conditions is an anthropogenic process applied with average results, but with process alternatives that can generate fuels as a means of bioremediation [51]. Results of research where this type of methods are applied in the degradation of plastics are shown in Table 3.

2.5.Wastewater treatment plants as a plastic removal measure

On the other hand, the identification of plastic removal methods as a decontaminating medium indicated through numerous studies that wastewater discharges are an important source of contamination in aquatic ecosystems due to their content of PMs and NPs. For this reason, treatment plants are considered a highly polluting source of plastics with discharges into rivers and lakes that end up connected to the ocean. Despite the fact that wastewater contains low levels of microplastics, the large volume of water to be treated means that the amount of plastic is enormous and is thus sufficient to cause significant damage to marine fauna and flora [101]. It is estimated that wastewater treatment plants release between 15,000 and 4.5 million particles of microplastics daily into surface water, representing 2% that could not be removed in the treatment process [95].

Table 3. Remediation methods reported for the reduction of plastics in experimental lab scale and real scale

Methods	Number of articles	Techniques used	Analyzed plastic	Results obtained	Reference
Advance oxidative	12	Photo-electrocatalytic degradation, photocatalysis, heterogeneous photocatalysis, photodegradation, traditional fenton, photo-fenton, heterogeneous photo-fenton, Fenton-like processes.	PS nanoparticles and PS, PE, LDPE, HDPE, PVC microplastics.	Photocatalytic degradation is the most studied process in advanced oxidation methods. This process is applied directly to catalysts such as TiO_2 or ZnO. Even so, the first is the most used and researched in terms of plastic degradation. It is applied with different modifications to achieve improvements in photocatalytic performance. Depending on the type of plastic, functional yields greater than 50% can be obtained. However, the preparation of the photocatalyst and the size of the particles to be degraded directly influence the final degradative result.	[54], [55], [59], [61], [62], [63], [76], [81], [82], [83], [84], [85]
Endothermic	10	Thermal treatments: Pyrolysis, co-pyrolysis, incineration, plasma arc gasification, catalytic hydrothermal cogasification.	PC, PET, PP, PS, LDPE, HDPE	Thermal methods are considered a viable option despite the fact that they can generate environmental contamination. According to the process and characteristics that persist within the application, the efficiency of these processes has generated percentages of up to 80% of the conversion of plastic contaminants into final products. The efficiency of the method depends on time, temperature, raw material (plastic), and adaptations to the process, being found in percentages of activity from approximately 60%.	[12], [51], [54], [60], [73], [86], [87], [88], [88], [89]
Indirect	17	Adsorption, membrane bioreactors, dynamic membranes, filtration technologies, agitation technologies, ozonation.	PP, PE, PS	Adsorption methods are the most abundant in this field of study. Wastewater treatments have shown percentages greater than 90% in the purification of plastic pollutants found in waters released into water systems, which can later flow into the oceans. Membrane technologies are the most promising for the release of these pollutants in water.	[31], [59], [62], [63], [73], [82], [89], [90], [91], [92], [93], [94], [95], [96], [97], [98], [99]

PE: Polyethylene; PS: Polystyrene; PVC: Polyvinilclorure; HDPE: Hight density polyethylene; LDPE: Low density polyethylene; PC: Polycarbonate; PE: Terephthalate de polyethylene; PP: Polypropylene

Wastewater treatment significantly reduces micro and nano plastics present in effluents. Plastics found in water treatment plants occur from primary and secondary sources. The primary sources are microspheres, granules, and fragments used in personal care and industrial adaptations. On the other hand, secondary sources are derived from larger plastics, promoting the presence of microplastics such as polymeric fibers from the textile industry [100]. The primary and secondary treatment processes remove between 75% and 91.9% of plastic particles. However, tertiary treatment increases this efficiency by 98% [100]. Wastewater treatment plants allow the elimination of between 88% - 90% of microplastics, being considered as an option to reduce the entry of plastic pollutants into water sources, either by direct or indirect discharge of water into the oceans [98].

Wastewater treatment has the frequent characteristic of working with activated sludge, capable of eliminating up to 67% of microplastics through enzymatic degradation exerted by microorganisms. Hyperthermophilic composting is, in turn, an application in the treatment of sludge with microplastics generated in wastewater, with promising results as a biological degradation method [63], [65].

2.6. Ocean protection policies and legal frameworks for future applications of the analyzed methods

Although plastic contaminant removal methods are an alternative for decontamination, a regulatory framework is needed. In this regard, some laws and projects try to reduce plastic waste regardless of its consumption. China, for example, maintains the Blue Bay Remediation Project that determines the restoration of the marine coast and where particular indicators are established for contamination of the area, tourism, population, and fauna, among others, to establish an action plan that manifests the recovery of the ecosystem. One of the goals of the project is to re-establish threatened species such as seagrass beds, coral reefs, kelp farms, and crust reefs in order to increase biodiversity [102]. Countries such as Italy, Slovenia, Croatia, Montenegro, and Greece have implemented pilot Garbage Fishing projects, which incorporate the meaning of the project as an activity in order to reduce the amount of plastic present in the area [103].

In the same way, global initiatives have been established to reduce the damage to the seas. The General Assembly of the United Nations (UN) has legislation on the Law of the Sea, while the United Nations Convention on the Law of the Sea (UNCLOS) forms an international legal framework that allows for controlling plastic pollution. On the other hand, the International Maritime Organization, the Food and Agriculture Organization of the United Nations (FAO), and the United Nations Environment Program (UNEP) participate in investigations related to solving the accumulation of fishing artifacts lost or abandoned as a decontamination measure in the oceans [32].

Plastic pollution found in water systems affects the quality of life of marine species. Plastic remediation processes help reduce the infestation of these materials in aquatic ecosystems to avoid considerable damage to species. Degradative methods are highly studied, but the reported yield rates indicate that changes are required to obtain better results. On the other hand, advanced oxidation processes and endothermic processes offer favorable results. Even so, methods focused on conversion promote the closure of cycles, the generation of fuels, or the revaluation of plastic waste itself, which could contribute to new technologies and advances within industries promoting the reduction of plastic pollution.

The application of removal methods is an alternative that varies depending on the expected results. Based on this criterion, research according to the theme should grow as strength to marine decontamination by plastics, emerging both in new applications and in modifications and even the combination of methods attracting progress to current studies. The constant limitations of the mentioned processes revolve around the degradation rates that they maintain living, organisms have high-performance rates, and the application of microbial consortia could increase degradation while accelerating the degradation time. On the other hand, with the application of the POA, results similar to those achieved with bioremediation could be obtained in short application times. Despite this, the disadvantages that this process could cause are not indicated. This same situation occurs in endothermic processes, so selecting one process over another could be conflictive without taking into account the total consequences of a method.

3. Conclusions

The systematic review reveals the existing problems due to pollution caused by plastics in the oceans. This situation is a cause for concern and a topic of interest in the scientific community, as reflected in the growing number of publications reported in recent years. About this, mitigation methods for plastic pollutants have been proposed ranging from bioremediation to chemical or transformation processes. The advanced oxidation processes that offer to degrade plastic pollutants present in marine ecosystems stand out, as well as the use of enzymes as a future alternative. However, one of the challenges to overcome in the use of these technologies is the correct scaling between the laboratory dimensions and real needs. Finally, joint action by world governments, multilateral organizations, companies, and the scientific community is required to establish policies and goals that protect the oceans, an ecosystem where the largest biological reserve of the terrestrial system is found.

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