

# Microplastic pollution in Costa Rican marine ecosystems: Origins, ecotoxicological impacts, and mitigation strategies

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## ABSTRACT

Microplastics (MPs) and nanoplastics (NPs) have become ubiquitous worldwide, posing complex challenges for marine organisms, ecosystems, and human health. In Costa Rica alone, approximately 4000 tons of solid waste are generated daily, of which about 11 % is plastic. Nearly 600 million single-use plastic bottles are produced yearly, with ~90 % not being collected. Consequently, reports of MPs in beaches, crustaceans, fishes, and bivalves are increasing on the Pacific and Caribbean coasts. Evidence suggests these plastic fragments can induce oxidative stress and inflammation in organisms, affect fundamental physiological processes (e.g., feeding, reproduction), and may even cross the blood–brain barrier. Recent policies in Costa Rica, including Law N°9786 (single-use plastics) and a proposed ban on MPs in cosmetics (Bill No. 23,694), mark progress. However, enforcement challenges remain—particularly given the country's limited wastewater treatment coverage. This review discusses key sources of MPs (e.g., wastewater, synthetic fibers, tire wear), current sampling and characterization protocols, and ecotoxicological consequences for marine life and humans. We further analyze existing legislation, highlighting gaps and prospective solutions, and propose an integrated approach involving technological upgrades, biodegradable polymers, and microbial degradation strategies to mitigate plastic pollution.

## 1. Introduction

Since the first report of microplastics (MPs) in the Sargasso Sea [9], the scale of plastic pollution has grown exponentially. This growth is reflected in the rapidly expanding body of scientific literature, from only a handful of studies in the 1970s to thousands of articles published annually in recent years. Microplastics (commonly defined as plastic fragments <5 mm in size [20]) and nanoplastics (NPs, <1 μm) have been detected in diverse marine environments, from surface waters to deep-sea sediments [2]. Global awareness has increased as evidence accumulates about the potential health risks linked to ingestion or inhalation of these particles, including oxidative stress, genotoxicity, and chronic inflammation [30,31,32]. Research indicates that microplastics (MPs) and nanoplastics (NPs) can adversely affect human health through various mechanisms. As Yu and Singh [76] emphasize, microplastic pollution significantly threatens marine biodiversity worldwide.

Humans are exposed to MPs through ingestion (via food and water)

and inhalation (airborne particles), leading to their accumulation in organs such as the liver, spleen, kidneys, and lungs [31,57,60]. Although less studied, dermal contact is another potential exposure route, especially in occupational settings [31,57].

MPs' toxicity is influenced by their size, shape, surface charge, and attached pollutants. These factors affect their ability to penetrate biological systems and cause harm [73,57,60]. MPs and NPs can directly damage cellular macromolecules like DNA, proteins, and lipids. This stress often results in chronic inflammation, a common feature in neurodegenerative, respiratory, and cardiovascular diseases [29,33,38,47,60]. DNA damage may lead to reproductive health issues and cancer development. This genotoxicity is both direct, through interactions with DNA, and indirect, via oxidative stress-induced reactive oxygen species (ROS) production by activating pathways like NF-κB and MAPK, exacerbating inflammation and oxidative damage, which can lead to hormonal imbalances and immune dysregulation [11,31,47,64].

In Costa Rica, the scientific investigation of MPs and NPs is still in its

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early stages. A country renowned for its biodiversity, Costa Rica faces unique socio-environmental conditions—a limited sewage-treatment infrastructure, inconsistent enforcement of plastic-related legislation, and high levels of tourism and coastal activities. Although the national government introduced regulations to address single-use plastics (Law N°9786) and has proposed a bill to ban intentional microplastics (Bill No. 23,694), the reality on the ground indicates considerable infrastructure and public awareness gaps.

Several recent studies have reported MPs in fish, crustaceans, and coastal sediments along both the Pacific and Caribbean regions [7,76], and the amounts detected are significant (e.g., up to 2900 MP fragments per m<sup>2</sup> of beach sand [78]). This review synthesizes the current knowledge on MPs in Costa Rican marine ecosystems, with a focus on the following objectives:

- **Detail the significant sources** of MPs/NPs relevant to Costa Rican coastal environments.
- **Analyze the ecotoxicological effects** of these plastic particles on marine organisms, with implications for human health.
- **Critically evaluate existing legislation and policies** regulating plastic pollution in Costa Rica, including their strengths and shortcomings.
- **Propose actionable mitigation strategies**, encompassing engineering tools, biobased polymers, and microbial degradation, informed by local and international case studies.

By consolidating this information, we aim to underscore the urgency of confronting plastic pollution in Costa Rica’s marine ecosystems and offer insights that may be applied in other tropical regions with similar socio-ecological contexts.

## 2. Materials and methods

### 2.1. Sampling of microplastics

Adequate sampling and identifying these particles are crucial for understanding their impact and developing mitigation strategies. The methods used to collect MPs vary depending on the environmental compartment (beach sand, surface waters, water column, sediments, marine organisms). A standard approach for beach sand involves collecting a measured volume or mass of sand in a quadrant, weighing it (wet), and drying it for filtration [56]. MPs are typically buoyed in a saline solution (NaCl or ZnCl<sub>2</sub>), allowing lower-density plastic particles to float while heavier debris sinks [52].

In offshore or nearshore waters, neuston nets are used for surface

tows at 1–5 knots, while submersible pumps can collect deeper water samples [77]. Sediment from the seafloor may be recovered via grabs, core samplers, or bottom trawls. Biological sampling (e.g., fish, bivalves) typically involves dissecting the gastrointestinal tract and flushing out contents or digesting soft tissues with 10 % KOH or strong oxidizers like hydrogen peroxide [7,12].

ISO/TR 21,960:2020 provides an overview of sampling protocols, physical and chemical separation methods, and analysis techniques but does not establish standardized protocols. Several relevant ISO norms were recently published, including ISO/CD 4484–1, which focuses on measuring fiber loss from fabrics during washing; ISO/DIS 4484–2, which addresses the qualitative and quantitative assessment of microplastics from textile sources; ISO/CD 4484–3, which pertains to measuring the mass of materials released from textile products during domestic washing; ISO/CD 24,187.2, which covers principles for analyzing plastics and microplastics in the environment; and ISO/AWI 5667–27, which relates to sampling microplastic particles and fibers in water. A broad array of protocols has been proposed and could be standardized in an ISO norm. Fig. 1 illustrates some relevant ISO standards.

For instance, the technological readiness for identifying NPs in environmental samples remains a significant hurdle. Current methods often lack the sensitivity required for detecting NPs at environmentally relevant concentrations, and there is a need for more robust and harmonized analytical techniques [14,69]. Developing receptor-based detection methods is promising, offering high specificity and the potential for portable, field-based applications [65]. There is also a need for developing portable and cost-effective detection methods that can be used in the field, as well as for conducting realistic experiments to assess the environmental and health impacts of MPs and NPs at actual environmental concentrations [48,68,69]. Further studies are needed to explore the toxicological effects of airborne MPs and NPs, particularly their impact on human health [14].

### 2.2. Purification and characterization protocols

Following sampling, organic matter is usually removed via chemical digestion (e.g., 10 % KOH, NaOCl), leaving plastic fragments. Size fractionation is achieved with sieves (commonly 25 μm–5 mm range). Microscopic examination (optical, SEM) helps quantify particle numbers and morphologies. Advanced spectroscopic methods—Fourier-transform infrared (FTIR), Raman spectroscopy—confirm polymer types, while pyrolysis-gas chromatography/mass spectrometry can identify plastic monomers and additives [12,25]. One practical approach involves filtration combined with surface-enhanced Raman spectroscopy

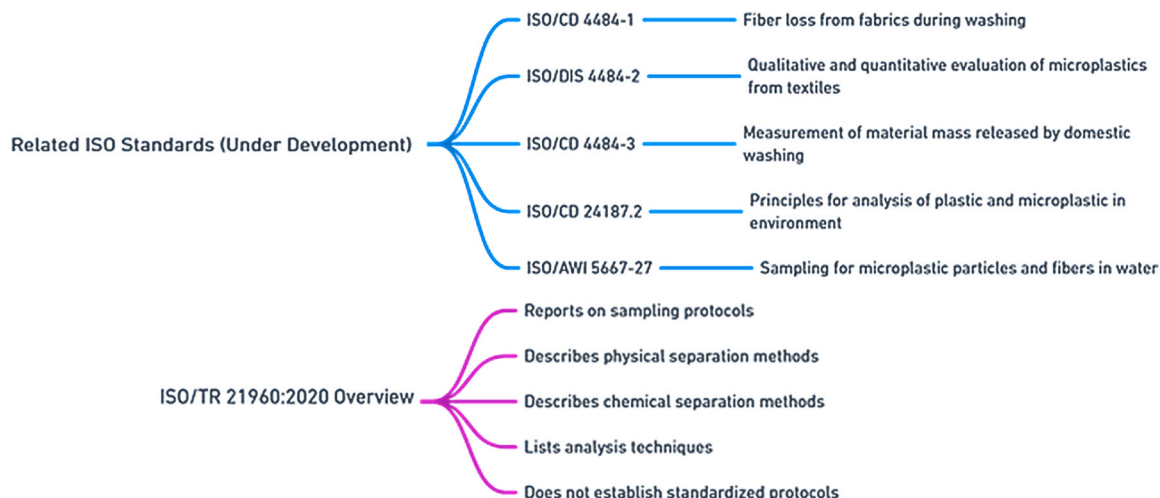


Fig. 1. Related ISO Standards.

(SERS), which allows for high retention rates and low detection limits for polystyrene MPs and NPs. This method also establishes a linear relationship for quantifying different sizes of MPs and NPs, making it a reliable method for mixed-size analysis [72].

Polymers such as polyethylene, polypropylene, polyethylene terephthalate, polystyrene, and polyamides are frequently identified in coastal and marine samples [7,45]. In some instances, energy-dispersive X-ray spectroscopy (EDS) is integrated with SEM to distinguish non-plastic debris from genuine plastic fragments based on elemental composition [7,25].

The characterization of NPs, particularly in atmospheric and aquatic environments, is more challenging than that of MPs due to their smaller size and distinct physicochemical properties. NPs exhibit stronger interactions with pollutants and have more adverse eco-impacts, necessitating advanced detection and characterization methods [13,34]. The lack of standardized sampling and identification protocols for nanoparticles further complicates the analysis, highlighting the need for harmonized methodologies [27,69].

### 3. Results and discussion

#### 3.1. MPs and NPs in Latin America

While the environmental and health impacts of microplastics (MPs) and nanoplastics (NPs) have received increasing scientific attention, regulatory responses in Latin America remain limited and fragmented. An in-depth regional assessment conducted by the Micro and Nano Allpa Pacha Network—comprising researchers from Chile, Peru, Colombia, Costa Rica, Ecuador, Panama, and Mexico—highlights national policies that address MPs and NPs as emerging pollutants. Instead, existing regulations focus narrowly on single-use plastics, with indirect or incidental relevance to plastic fragmentation and micro-contamination. This regulatory gap contrasts with international examples, where jurisdictions such as the European Union, Canada, and the United States have begun implementing restrictions on intentionally added microplastics in consumer products [57].

In Colombia, for instance, Law 1973 (2019) prohibits the entry, commercialization, and use of certain plastic materials in the San Andrés Archipelago. Resolution 1407 (2018) establishes environmental protocols for managing packaging waste made of plastic and other materials. Chile enacted Law 21,368 (2021), which regulates the distribution of single-use plastics and disposable PET bottles to reduce waste generation and encourage sustainable alternatives. Ecuador has implemented subnational ordinances in the Galápagos Islands that restrict expanded polystyrene and other disposable plastic products. Although Costa Rica lacks direct legislation on MPs and NPs, it has taken steps toward regulatory action by promoting public sector bans on polystyrene and participating in regional and international panels addressing nanomaterial governance, particularly in food safety and public health [40].

At the regional level, the Presidential Declaration on the Sustainable Management of Plastics—signed during the 2019 Pacific Alliance Summit by Chile, Colombia, Mexico, and Peru—reflects growing political will for joint action, though implementation remains largely aspirational. Globally, [44] emphasize that standardized monitoring and integrative frameworks are necessary to mitigate marine plastic pollution.

This situation is summarized in Table 1, which presents a comparative overview of the most relevant national and regional regulatory instruments related to plastics and their indirect implications for MPs and NPs [40,67,70].

##### 3.1.1. Findings in Costa Rican coasts

The investigation of microplastics (MPs) and nanoplastics (NPs) in Costa Rica is a growing area of scientific research, reflecting global concerns about plastic pollution and its impact on marine ecosystems.

**Table 1**  
Overview of national regulations related to plastics and their relevance to MPs and NPs in Latin America. [40,70]

| Country    | Regulation or Initiative   |
|------------|--|
| Argentina  | Law 27.602 (2020): Prohibits the production, importation, and commercialization of cosmetic and oral hygiene products containing intentionally added plastic microbeads. |
| Brazil     | Lacks comprehensive national legislation on plastic production and waste management despite being the region's most prominent plastic producer.                          |
| Colombia   | Law 1973 (2019): bans entry and use of certain plastics in San Andrés  |
| Colombia   | Resolution 1407 (2018): environmental management of packaging waste  |
| Chile      | Law 21,368 (2021): regulates single-use plastics and disposable PET bottles  |
| Ecuador    | Galápagos ordinance: restricts disposable plastics and expanded polystyrene  |
| Peru       | Signatory of 2019 Pacific Alliance declaration on sustainable plastics management  |
| Costa Rica | Institutional initiatives on polystyrene; participation in Codex panels  |
| Mexico     | Signatory of Pacific Alliance; member of Allpa Pacha Network   |
| Panama     | No specific regulation; regional participation through Allpa Pacha Network   |
| Uruguay    | Law 19.655 (2018) promotes reducing the use of plastic bags and replacing them with reusable or biodegradable alternatives.  |

This research is crucial for understanding the extent of pollution and developing strategies for mitigation and management. As shown in Table 2 and Fig. 2, significant amounts of microplastic pollution have been found in marine ecosystems in Costa Rica, particularly along the Pacific coast.

A study found that MPs were present in 100 % of certain bivalve species, with varying levels in others, indicating widespread contamination in marine life. The study highlighted that fibers and particles were the predominant forms of MPs found in these species, marking the first such investigation in Central America's Pacific region [54]. Despite Costa Rica's global reputation for environmental stewardship, quantitative data on MPs remains fragmentary. Costa Rica's commitment to conservation is evident in its management of marine protected areas (MPAs). The success of MPAs is influenced more by social factors than physical ones, highlighting the importance of public participation and adaptive management. Evaluations of MPAs in Costa Rica show varying levels of success, with some areas demonstrating proactive management and others requiring improvements. Continuous evaluation and

**Table 2**  
Summary of reported MPs in various Costa Rican marine environments.

| Study Location                                | Concentration & Key Findings  | Polymer Types Identified       | Ref. |
|---|---|--------------------------------|------|
| Las Baulas Marine National Park, Guanacaste   | Up to 2.64 MP items per crustacean ( <i>Callinectes arcuatus</i> ) and 3.75 MP per pelagic fish | Not available                  | [5]  |
| Cocos Island National Park                    | ~1.4 MPs/freshwater fish; ~3.3 MP/kg sediment in marine zone                                    | Not available                  | [4]  |
| Central Pacific (Opisthonema complex herring) | ~37 MP items/fish   | Polypropylene, polyethylene    | [7]  |
| Gulf of Santa Elena, Guanacaste               | ~0.1 MP items/L surface water; ~2.5–2.8 MP items/fish (various species)                         | Not available                  | [23] |
| Pacific Thermal Dome                          | 206 MPs over 13 sites (80 m sampling distance)  | Not available                  | [28] |
| Puntarenas (beach sand)                       | Up to 2900 MP/m <sup>2</sup> in top 1 cm of sand  | PET, PP, nylon, polyamides     | [56] |
| Gulf of Nicoya (bivalves)                     | 2.1–22.4 MPs per individual, depending on location  | PET, PE                        | [54] |
| Caribbean and Pacific beaches                 | 209–2961 MP/kg in the Pacific, 258–479 MP/kg in the Caribbean                                   | Styrofoam, pellets, and others | [42] |

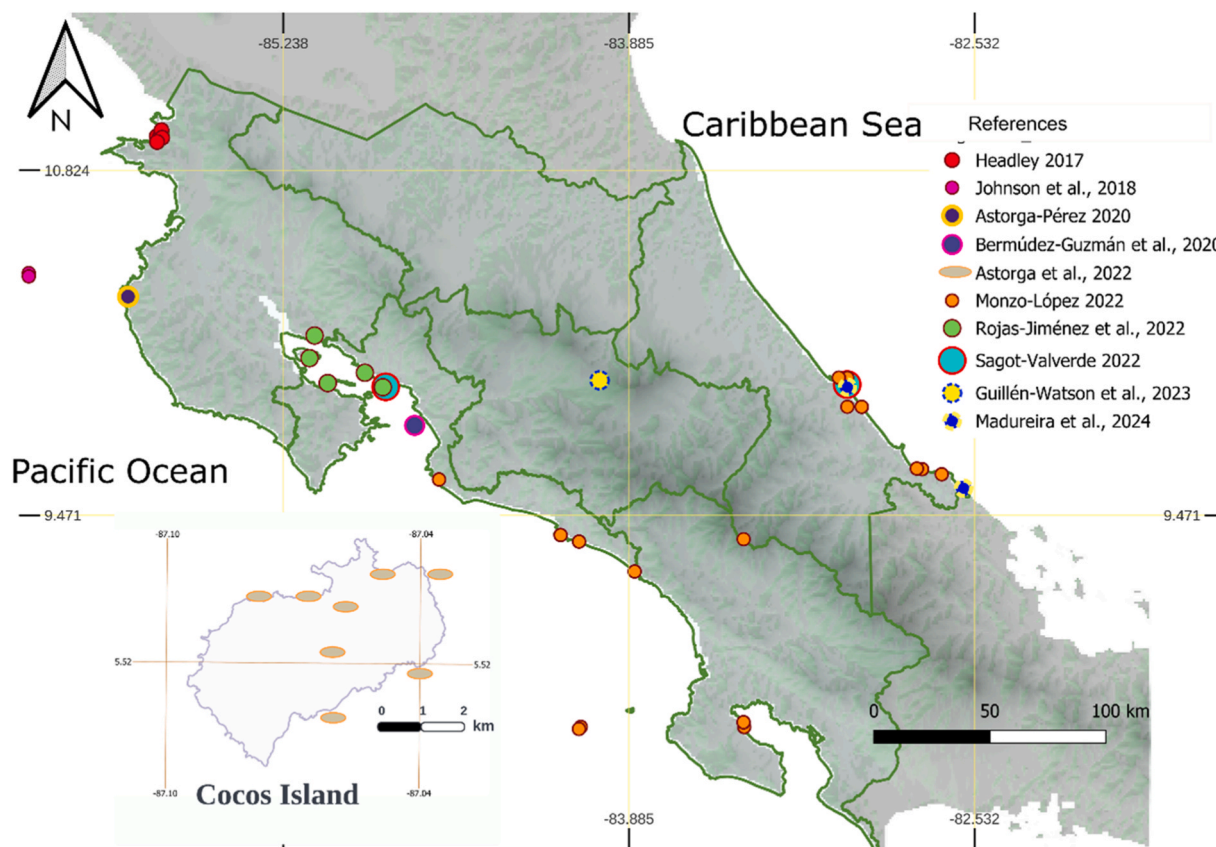


Fig. 2. Locations of MP samplings reported in the literature in Costa Rica.

feedback are crucial for effective MPA management [37]. Table 2 summarizes published reports, and Fig. 2 shows the approximate location of the reports cited here.

Costa Rica’s daily waste production (4000 tons), of which 11 % is composed of plastics [17], underscores why macroplastic debris—and hence secondary MPs—are widely detected. In some regions, localized sources (e.g., untreated sewage, industrial outfalls) enhance MP loads. Further complicating matters, ~76 % of households rely on septic tanks rather than centralized wastewater treatment [6].

Most of the sampling efforts have been carried out on the Pacific coast; the Caribbean coast samplings are restricted to the southern

region, with no sampling of MPs to date for the North Atlantic coast. Cocos Island is shown on the bottom left inset. A study by Guillén-Watson et al. [21] is shown in the map as the first report on the direct effects of MPs on freshwater life in Costa Rica. They studied the crayfish intestinal microbiome and immune system health by determining phenoloxidase (PO) activity, demonstrating the prevalence of opportunistic pathogenic bacteria genera after ingesting food mixed with PET with decreased PO immune response.

Table 3  
Representative biological impacts of MPs/NPs across trophic levels.

| Trait   | Producer   | Consumer  |   |   |
|---|--|---|---|---|
|   | Primary  | Primary   | Secondary   | Tertiary/Quaternary   |
| [*Growth/reproduction]<br>[* *Behaviour/Morphoanatomic]<br>[* **Metabolism] | [*Shoot/Root length reduction/<br>Extracellular polymer damage, cell<br>pore blockage, impact on microbial<br>communities of roots, altered<br>structure of photosynthetic<br>complexes, Rubisco activity<br>suppressed] [* *Bioaccumulation,<br>synergistic effect damage on cell<br>membrane] [* **Nutrient/water<br>availability and photosynthesis<br>machinery damage, changes in<br>proportional synthesis of cellular<br>pigments, increased ROS by high<br>enzymatic activity, genes<br>dysregulation] | [*Filtration rate reduction,<br>decrease reproduction and<br>defenses, adult mortality-<br>adverse embryonic effects,<br>damage in gastrointestinal<br>walls] [* *Deformities in larval<br>mandibles, mentus and wings<br>development] [* **Alteration of<br>gut microbiome, phenoloxidase<br>activity reduction, reduced food<br>intake and excretion] | [*Decreased growth, DNA damage,<br>mutagenic and cytotoxic<br>processes] [* *Neurotoxicity,<br>locomotion issues, anxiogenic<br>effect symptoms, anti-predatory<br>defensive response, liver: blood<br>vessel dilation, infiltration,<br>congestion, hydropic<br>degeneration, pigmentation<br>disorders, allometric<br>abnormalities, changes in nuclear<br>shape and size][* **weight loss,<br>changes in cholesterol ratio in<br>serum and its distribution between<br>muscle and liver tissues, gut<br>microbiota dysbiosis, changes in<br>gene expression] | [*Presence in placenta (humans),<br>reduced cell viability, reduced<br>sperm motility and production,<br>testicular weight decreased,<br>ovarian inflammation] [* *Severe<br>toxic effects in the intestine, and<br>liver tissue (fishes) with the<br>highest lethality]<br>[* **Disturbance of lipid<br>metabolism, endomembrane<br>system destabilization can affect<br>Internalization in different<br>cellular types, genotoxicity] |
|   | [10,41,62]   | [10,21,36,41,62]  | [10,21,36,41,49,62]   | [10,21,24,36,41,43,53,58]   |

3.2. Ecotoxicological effects on marine organisms and humans

3.2.1. Impacts on marine biota

Microplastics and nanoplastics affect marine organisms spanning primary producers to higher trophic levels [26,41]. Table 3 condenses the principal effects of MPs on different trophic levels. From aquatic and marine life to terrestrial life, the transfer of these materials occurs through trophic dynamics [15]. Fig. 3 For long-lived species such as sea turtles, Darmon et al. [16] showed debris ingestion is influenced by behavioral and ecological drivers over decades.

Their small size allows ingestion or adhesion to cell surfaces, causing:

- **Physical Blockage & Reduced Feeding Efficiency:** Filter feeders (e.g., bivalves) can accumulate MPs in the digestive tract [54]. Similar ingestion rates have been observed in Moroccan coastal fish species, as Bouzekry et al. [8] reported, raising concerns about trophic transfer to humans.
- **Oxidative Stress & Inflammation:** MPs and NPs can produce reactive oxygen species (ROS), damaging lipids, DNA, and proteins [39].

- **Biochemical Disruption:** Observed reductions in key enzymes (e.g., Rubisco in microalgae), potentially altering photosynthetic performance and nutrient cycling [62].

3.2.2. Potential human health risks

Human exposure to MPs/NPs occurs via inhaling contaminated air or consuming seafood and water [35]. Polystyrene NPs (<500 nm) can be internalized by endocytosis, potentially disrupting lysosomal membranes [19]. Studies have detected plastic particles in human placentas [53] and even suggested possible translocation across the blood-brain barrier [30]. Chronic exposure may aggravate inflammation, immune responses, and other pathophysiological outcomes [74,75].

MNPs (Micro- and Nanoplastics) can enter the human body through inhalation or ingestion [35], crossing barriers like the intestinal lining or lung tissues and spreading to organs such as the spleen, liver, and kidneys. Their toxicity depends on their size, type, and physical properties [19]. For example, polystyrene particles, especially those smaller than 500 nm, can enter cells via endocytosis, causing cellular damage through the generation of reactive oxygen species (ROS) [75]. The positive charges in these particles can induce damage to cell membranes. Diffusion of polystyrene MNP occurs rapidly through different types of

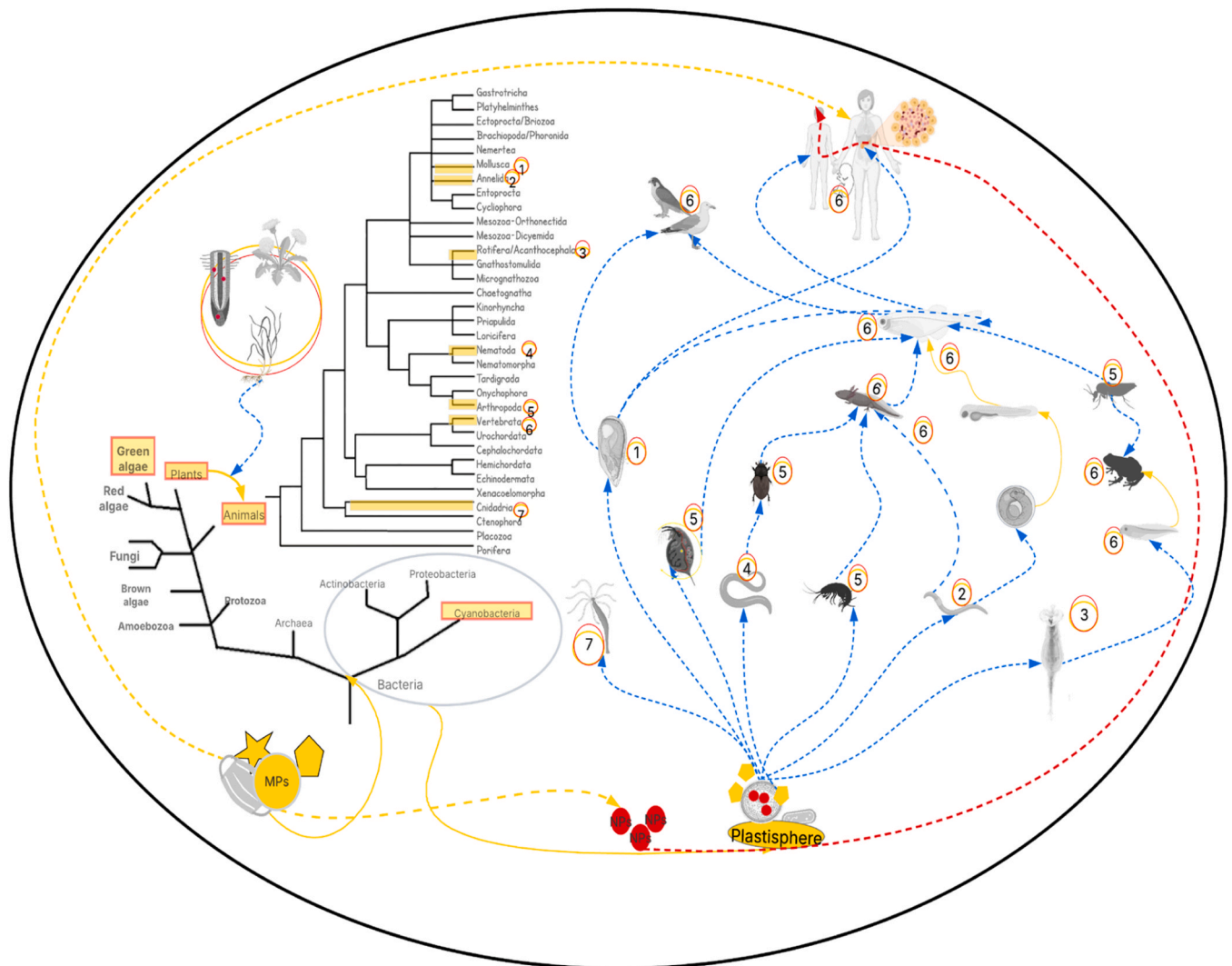


Fig. 3. Simplified schematic relationships between the aquatic/marine life and incidence of MNPs through trophic transference. Tree of Life shows the biological kingdoms on which studies have been carried on MNPs (yellow-red boarded squares) and a more detailed animal phylogeny (Modified from [66]) showing the phyla sampled for MNPs analysis (yellow underlined and numbers associated with graphical examples) reported in the literature. Yellow indicates MP fluxes, and red (red dotted lines) shows NPs fluxes. Blue arrowed lines show the biomass trophic transfer. Interaction (intersections) between different color lines indicates coexistence or derivation. Created with BioRender ([www.biorender.com](http://www.biorender.com)) and LucidChart ([www.lucidchart.com](http://www.lucidchart.com)).

cells, including those of the liver. These particles can disrupt mitochondrial function, leading to inflammation and genotoxicity; larger particles may escape from lysosomes after endocytosis, causing further damage often masked by apoptosis [32]. Additionally, the presence of immune cells like leukocytes can mitigate inflammation in the intestines compared to other organs. A review by [3] highlights the increasing public health risks of MNPs, stressing the importance of shifting toward a circular economy to reduce their ecological and health impacts. This is consistent with findings by Akbari and Jaafari [1], who provided a comprehensive overview of microplastic-induced risks to marine organisms and their cascading effects on human health.

### 3.3. Legislation and policy in Costa Rica

Costa Rica has enacted legislation (Law N°8839, Law N°9703, and Law N°9786) for an integral management of waste, to curtail expanded polystyrene packaging, and limit single-use plastics. However, enforcement remains inconsistent. Technical rules that would standardize quality and composition of bottles, as well as those of bags are under discussion, as is the mechanisms to verify quality and compostability. Proposed Bill No. 23,694 includes banning the import, production, marketing, distribution and export of cosmetic or cleaning products that contain microplastics; in the case of non-cosmetic products that require MPs, it enforces mandatory MPs labeling; it also includes tax incentives for the import and production of filters that help to collect these microplastics, and allocates budget for research projects to substitute plastic microparticles.

Regarding reducing secondary microplastics from macroplastic origin, Costa Rica ratified Law N° 9786 in 2023, which bans since April 2024, the commercialization of single-use non-biodegradable plastic bags and straws. with fines to be enforced beginning July 2025. Plastic bottle suppliers must ensure at least one of the following: a) include recycled plastic in the bottles, b) establish an effective reuse, recoup, or recycling program, c) partake in waste management programs, d) produce minimal waste bottles, e) establish waste management, strategic alliances with at least one municipality.

Only ~14–21 % of wastewater is centrally treated [6], leading to direct discharge of greywater containing microfibers from laundry machines, personal care products, and industrial sources. Environmental agencies in the country have limited inspection capacity and budget constraints. Collaborative programs with NGOs (MarViva, OneSea) may boost public awareness and mobilize local communities to reduce plastic waste at the source, but bridging the gap between legislative intent and real-world compliance is crucial, for which public and private efforts in education and waste minimization culture are of uttermost importance.

### 3.4. Remediation techniques

Technological remediation strategies can be divided into (i) engineering tools, (ii) the use of biobased or biodegradable polymers, and (iii) biotechnological tools [51].

#### 3.4.1. Engineering solutions

Current wastewater treatment plants offer the possibility to implement microplastic removal via membranes, electrocoagulation, and agglomeration. In a typical wastewater treatment plant, pretreatment consists of large solids and oils removal through screens and grit chambers. It is followed by primary treatment in a settling tank where the solids are removed in a sludge that sinks to the bottom. Microorganism-activated sludge is commonly used as a secondary treatment to decrease organic components, and optional tertiary treatments can consist of membrane or sand filtrations [63]. Compiled efficiencies in removing microplastics in current wastewater treatment plants show a typical overall retention of over 90 % [22].

Subsidiary strategies are being considered worldwide to reduce MPs' outflux further. Ouda et al. [46] recently reviewed the degradation of

MPs via photocatalysis. Photocatalysis uses semiconducting materials, such as titania or zinc oxide, whose electrons are excited by light, causing the generation of reactive oxygen species (ROS) that induce the degradation of adsorbed materials. Their compilation of results from several studies using different conditions shows up to 70 % degradation of non-biodegradable microplastics in hours.

A filter cartridge for domestic laundry machines is now on the market (Planetcare.org), and another will soon be available (<https://www.gulp.online/>), both of which catch the MPs released from the clothes being washed. The used cartridges can be emptied and reused, or the collected material can be shipped back to the supplier for storage and eventual reuse/recycling into insulation mats, and the cleaned filter cartridges are then shipped back to the customers.

Alternate methods under R&D are giving promising solutions at the lab scale: electrocoagulation, where metal electrodes release coagulant ions in situ, is a simple and robust method that has been found effective in small tests (1 L), with removal efficiencies above 90 %, across pH values from 3 to 10 [69]. Agglomeration is another plausible strategy. For example, Sarcletti et al. [59] proposed employing core-shell superparamagnetic iron oxide nanoparticles that attract nanoplastics to form larger agglomerates removed via an external magnetic field. Although the authors hypothesize that the plastic waste could be melted away from the thermally stable superparamagnetic nanoparticles for plastic recycling and nanoparticle reuse, this has yet to be demonstrated. As described by Eswar et al. [18], nanotechnology-enabled strategies offer promising routes for mitigating microplastic pollution at the molecular level. Urso et al. [71] propose using self-propelled multilayered titania decorated with magnetic nanoparticles to trap nanoplastics and determine nanoplastics concentration when probed through electrochemical detection. Trapped nanoplastics can be released by raising the pH of the medium from 3 to 11. It is expected that in the coming years, strategies like the ones above will see increased testing under natural wastewater conditions to better assess implementability.

#### 3.4.2. Biobased and biodegradable materials

These can be classified into a) biobased non-biodegradable, b) biobased and biodegradable, and c) fossil-based biodegradable (Fig. 4). Biobased polyethylene (bio-PE), polypropylene (bio-PP), and polyethylene terephthalate (bio-PET), among others, fall under the first category as long as at least one of the molecular components is from a renewable source. These will only reduce persistent MPs presence and continue accumulating if better recycling efficacy, safety, and industrial chemical degradation are implemented. Polylactic acid and polyhydroxyalkanoates are in the second category, biobased and biodegradable, displaying two desirable properties for modern plastics. These examples are industrially compostable and must first be collected for proper decomposition. If improperly managed, they will contribute to MPs pollution: they will take decades to degrade and, in doing so, will generate secondary microplastics. New solutions have appeared for specific applications, such as mushroom-based packaging materials (e.g., Ecovative). Examples of fossil-based but biodegradable materials include polybutylene adipate terephthalate and polycaprolactone diol. The biodegradability can now be certified via European Standard EN 13,432 and US Standard ASTM D6400–99, which require specific composting conditions in their protocols.

#### 3.4.3. Microbial and enzymatic degradation

Bacteria and fungi capable of degrading plastics (especially PET) through specialized enzymes (e.g., PET hydrolases, cutinases) are under study [55,61]. Fig. 5 illustrates a generalized pathway wherein abiotic factors (UV exposure, temperature) create surface cracks, facilitating microbial colonization and enzyme-mediated breakdown to simpler molecules (CO<sub>2</sub>, H<sub>2</sub>O, biomass). Recent studies focus on genetically engineering microbes to degrade MPs faster and more thoroughly [46]. Practical implementation requires scaling from lab-based processes to industrial or municipal waste streams, where high organic loads or

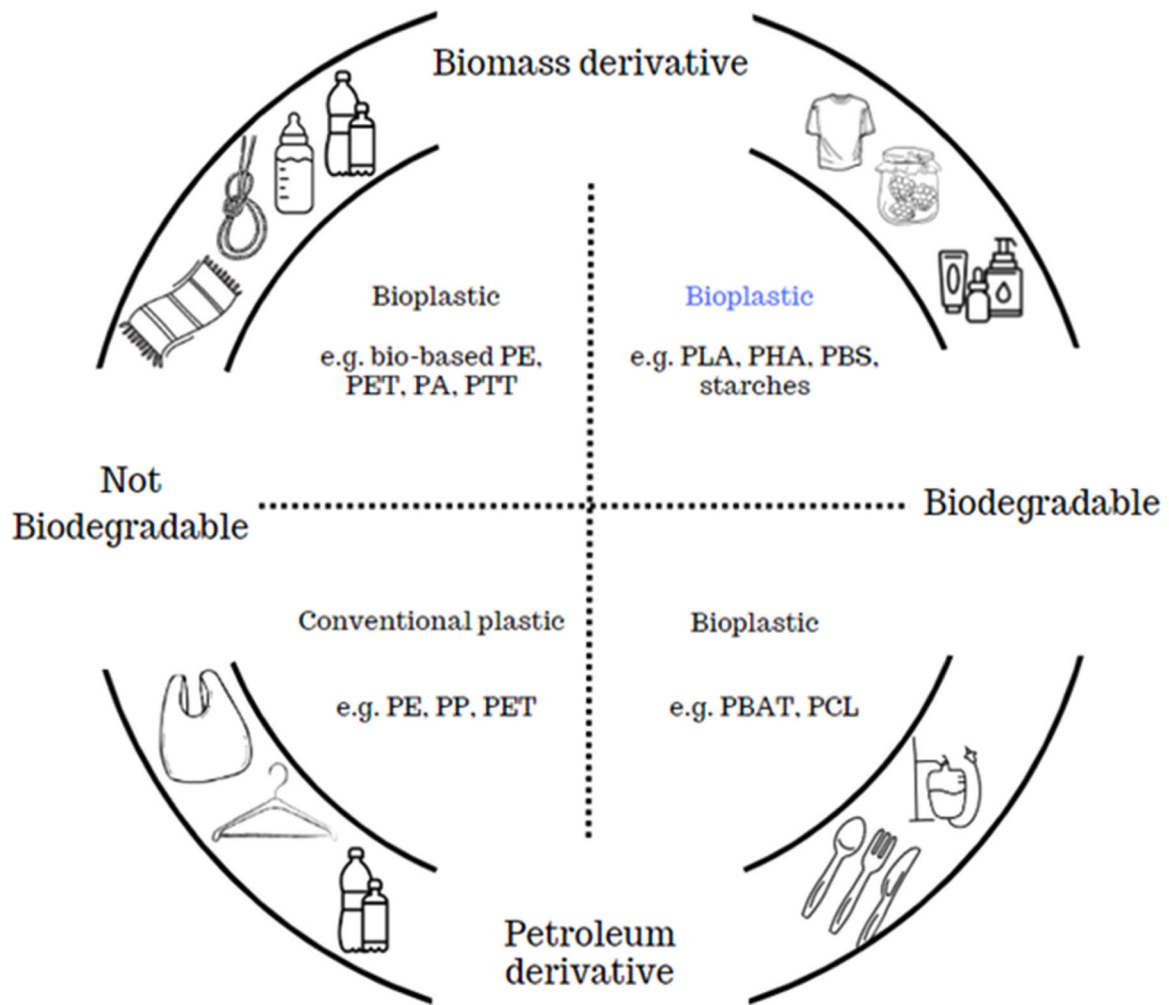


Fig. 4. Classification of biobased and biodegradable plastics. On the left quadrants, non-biodegradable plastics of biological origin (top) and petroleum-derived (bottom). On the right quadrant, biodegradable plastics of biological origin (top) and petroleum-derived (bottom).

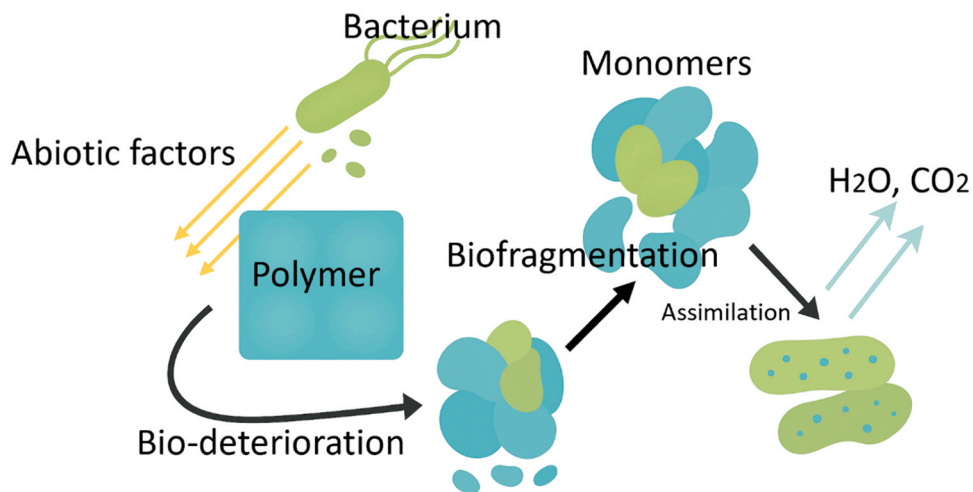


Fig. 5. Scheme of plastic biodegradation by bacteria, emphasizing abiotic factors influencing the degradation rates and the steps required for complete polymer degradation. It is reproduced with permission from Sheth et al. [61] via a Creative Commons Attribution License (CC BY).

chemical inhibitors may hinder biodegradation rates.

#### 4. Conclusion and outlook

This review consolidates current evidence on microplastics and nanoplastics in Costa Rican marine ecosystems, tracking their sources,

prevalence, and documented ecotoxicological effects. We also appraised national legislation limiting plastic pollution—though enforcement gaps reveal a need for more robust infrastructure and policy coherence. The four objectives outlined in the Introduction are addressed:

- Sources:** Primary pollutants include tire wear, synthetic fibers, personal care products, and macroplastic fragmentation.
- Ecotoxicological Effects:** MPs/NPs can impair the physiological and cellular functions of aquatic life, ultimately threatening human health through trophic transfer.
- Legislation Gaps:** Laws N°8839 and N°9786 and the proposed Bill No. 23,694 underscore governmental resolve, yet wastewater treatment coverage remains critically low.
- Proposed Mitigation:** An integrated strategy spanning (a) engineering upgrades for MP removal, (b) adoption of biodegradable/bio-based polymers, (c) microbial/enzymatic bioremediation research, and (d) comprehensive public education.

Mechanistically, plastic particles—especially at the nanoscale—can enter cells via endocytosis, damaging organelles and triggering reactive oxygen species that disrupt lipid membranes and enzymes. This can manifest as inflammation, immunological dysregulation, and adverse reproductive outcomes, underscoring the urgency of intervention.

In the coming years, it is imperative to strengthen research on microbe-based plastic degradation, upgrade municipal waste-management systems, and foster consistent enforcement of plastic regulations. To trace the detected MPs back to the source, a more detailed analysis of the detected MPs is suggested. By bridging scientific evidence with policy actions, Costa Rica—and other nations facing similar challenges—can safeguard marine biodiversity and public health.

#### Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jose Vega Baudrit reports administrative support and article publishing charges were provided by National Nanotechnology Laboratory. JOSE VEGA BAUDRIT reports a relationship with National Nanotechnology Laboratory that includes: board membership. JOSE VEGA BAUDRIT has patent — pending to —. — If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Data availability

No data was used for the research described in the article.

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