



Review

Microplastics in the marine environment: Challenges and the shift towards sustainable plastics and plasticizers

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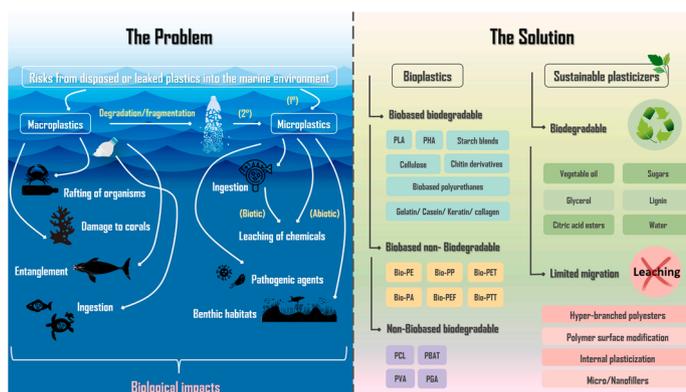
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HIGHLIGHTS

- Plastic waste has become a major threat to all species in the marine environment.
- Microplastics were detected in the cryosphere, atmosphere and hydrosphere.
- Leaching of plasticizers threatens marine biodiversity, disrupting entire ecosystems.
- A comparison between all types of bioplastics regarding their effectiveness in reducing debris contamination.
- Plant oils offer a sustainable alternative to petrochemical-based plasticizers.

GRAPHICAL ABSTRACT



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ABSTRACT

The United Nations (UN) estimate that around 75–199 million tons of plastic is floating in the world's oceans today. Continuous unintentional disposal of plastic waste in marine environments has and continues to cause significant biological impacts to various marine organisms ranging from mild difficulties in swimming or superficial damage to critical organ malfunctions and mortality. Over time, plastics in these environments degrade into microplastics which are now acknowledged as a pervasive harmful pollutant found in the cryosphere, atmosphere and hydrosphere. In response to this issue, the production of bespoke biodegradable bioplastics derived from renewable resources, such as vegetable oils, starch and plant fibres, is emerging to mitigate our reliance on environmentally persistent conventional fossil fuel-based plastics. While bioplastics degrade more readily than conventional plastics, they present new challenges, including leaching of toxic chemical additives and plasticizers into the environment. Consequently, various techniques have been explored in the search for sustainable plasticizers, from cheap, non-toxic compounds, such as vegetable oils and sugars to hyperbranched structures with limited migration. This article seeks to explain the intricate relationship between the problem of microplastics in marine environments and the strategies that have been investigated to address it thus far.

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1. Plastic pollution and bioplastics as a possible solution

Since the 1950's, plastics have become the foundation of modern-day industry, defining the very fabric of our daily lives. The production of plastic took only 70 years to reach over 400 million tons per year with an increasing annual growth rate of 3% [1–3]. In 2025, it has become impossible to avoid the incorporation of plastic into almost every industry – owing to their versatility, low weight, and low production costs – from transport, electronics, communication, computers, medicine to food packaging and energy production [4–8].

Through polymerization or polycondensation processes, non-renewable fossil fuels such as oil and gas can transform into plastic polymers [9]. Polyethylene (PE) from ethylene, polypropylene (PP) from propylene, polystyrene (PS) from styrene, and poly(vinyl chloride) (PVC) from vinyl chloride are some of the most commercially used polymers today [10]. Although these synthetic plastics come from non-renewable resources, their value lies in their durability, being highly durable and almost indestructible. Some of these plastics are single-use plastics, and as the demand for them increases yearly, this has led to a growing accumulation of plastic waste in the environment, especially marine environments, often through accidental loss, inadequate disposal and wastewater discharge [11,12]. The predicted fate of plastics produced across the globe between 2019–2060 is depicted in Fig. 1 [13]. In the past decade, scientists and environmental managers have acknowledged the urgent need to comprehend the biological impacts of these enduring synthetic polymers.

Despite current efforts to address the challenge of plastic disposal, the United Nations (UN) estimate around 75–199 million tons of plastic is floating in the world's oceans [14]. Plastics are resistant to degradation, which means they take decades to a millennium to completely disappear, however, they are subject to fragmentation over this time due to the effects of UV radiation, wave action, and physical and chemical interactions with marine organisms [15]. Although plastic itself is a chemically inert material, through fragmentation into smaller particles less than 5 mm in diameter, referred to as microplastics (MPs), synthetic polymers pose a significant threat. The fragmentation process can release harmful chemicals - originally incorporated within the polymer as additives to impart desired qualities - directly into the environment [16]. Through this mechanism, MPs have significant biological effects, affecting not only organisms but also human health. Studies have shown that MPs can affect marine life significantly by altering animal's feeding behavior, their growth and reproduction, causing inflammation, and altering their genes and protein expression [14,16,17]. The consequences of MPs have extended to human health, having been shown to infiltrate the human body via inhalation or absorption, and accumulate in various organs, including in lungs, spleen, kidneys, liver, and recently, in the placentas of newborn babies [18–25]. Other implications on the economy such as environmental clean-up costs, aquaculture stock contamination, and the effect on tourism are also being studied and assessed by governments and researchers [26,27].

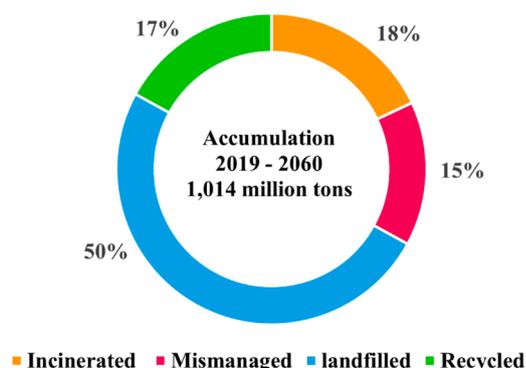


Fig. 1. Plastic waste accumulation projection from 2019 to 2060 [13].

MPs are now recognized, in their own right, as a serious global problem. In an effort to solve the issue or reduce its implications, researchers have started to think innovatively of more rapid and efficient ways to deal with this persistent plastic problem, thus introducing the idea of bioplastics. So far, the term “bioplastics” has been flexible enough to include plastics that are either made of renewable resources or made via biological and/or sustainable processes. In this context, some biodegradable plastics derived from fossil fuels are also categorized as bioplastics (i.e., made of fossil fuels but contain additives that cause them to decay more rapidly in the presence of light, heat, moisture and oxygen [28]), such as PE, PP and PS which are fossil fuel-based polymers modified through the addition of transition metals (e.g., iron, manganese, cobalt) to the polymer blend making them oxo-biodegradable [29–31]. Currently, some of the most common bioplastics on the market include polylactic acid (PLA), polybutylene succinate (PBS), poly(butylene adipate-co-terephthalate) (PBAT), and polycaprolactone (PCL). There have been attempts to phase out the use of petroleum-based plastics by replacing them with bioplastics, however, this has been impeded by many challenges, including higher production costs and poorer performance that continues to limit their viability as materials [32]. Nevertheless, there is a growing demand for bioplastics to help achieve the Sustainable Development Goals (SDGs) of the UN, evident by the production of about 2 million tons per year of 100% biobased plastics and with an expected growth rate of 30% annually [28,33].

While biobased materials are designed to fragment and degrade, like their plastic counterparts they have the potential to leach harmful and toxic chemical additives incorporated within the plastic composition, especially plasticizers [34]. Phthalate esters such as dioctyl phthalate (DOP), di(2-ethylhexyl) phthalate (DEHP), and diisononyl phthalate (DINP) are currently the most extensively used plasticizers. Although their use is widespread, their chemical properties are associated with several health and environmental concerns including negative effects on various living organisms [35–37]. Therefore, new trends in research and development favor the introduction of more sustainable plasticizers and, indeed, many studies have already explored the possibility of making plasticizers from biobased and environmentally friendly resources such as vegetable oils, biobased esters, and even glycerol [33,38,39].

It is evident from the existing literature that while numerous review articles provide coverage of marine pollution or discuss the ways in which sustainable polymers and additives can solve the plastic issue [33, 40–42], there is a conspicuous absence of comprehensive reviews that link both topics and provide a holistic view with a focus on the impact on marine life. This article seeks to bridge that gap by presenting an integrated perspective on the current challenges posed by MPs, particularly in the context of recent studies conducted from 2021 to 2024. This period includes the COVID-19 pandemic which triggered a significant increase in plastic production and usage, resulting in a heightened (unintentional) disposal of plastics into aquatic systems [43–46]. Our discussion highlights the magnitude of this issue today, emphasizing the urgent need for solutions that prioritize the health of marine environments. Furthermore, we provide a thorough examination of the most promising sustainable polymers and plasticizers currently emerging on the market. By establishing recent advancements and innovations in this field, we aim to create a valuable resource for researchers dedicated to the development of new sustainable plastics and additives. This article not only interprets the pressing nature of marine pollution but also presents a viable starting point toward future investigations for a modern solution.

2. Methods

Literature in this narrative review article was collected from databases including Web of Science, PubMed and Google scholar. A search for studies published from 2021 to 2024 was prioritized to ensure the inclusion of the most recent data. According to the topic, terms such as

(marine pollution, plastic pollution, sea litter, microplastics, microplastics count, bioplastics, biodegradable plastic, sustainable plasticizers, plasticizer toxicity, leaching of plasticizers) were used. When no relevant studies were found within this period, the search was progressively expanded year by year, going back to include studies published 2020, 2019, and so on, until relevant studies were identified. Articles unrelated to our research topics or written in any language other than English were excluded. All articles were thoroughly examined and sourced from reputable journals.

3. Microplastics in marine ecosystems: abundance, impact, and leaching

3.1. The problem and the magnitude

Microplastics are typically defined as plastic particles with a size ranging from 5 mm to 10 μm . Based on their origin, they can be classified as either primary or secondary MPs [41]. Primary MPs are deliberately produced as micron-sized particles and are frequently used in cosmetic exfoliants, textile treatments, sandblasting media, synthetic garments, and industrial abrasives [47,48]. They are introduced into the oceans via runoff or wastewater discharge. On the other hand, secondary MPs derived from the degradation and fragmentation of macro- or mesoplastic items and are mostly formed in the environment, including the oceans.

Because MPs can exist in a range of sizes and morphologies, they are now acknowledged as an omnipresent and pervasive harmful pollutant. They are found in terrestrial, freshwater, and marine environments, and even in the most unexpected places such as ice and recently on mountain tops worldwide [49]. Studies in the cryosphere revealed the first reported evidence of MPs in the supraglacial debris in 2019, the study estimating that the Forni Glacier (Italian Alps) area hosts 131–162 million plastic items (74.4 ± 28.3 items kg^{-1}), most of which were identified as polyester, polyamide, polyethylene, and polypropylene [50]. In 2024, a study performed in Alaska revealed high MP counts in the state's snow (681 ± 45 L^{-1}), lakes (361 ± 76 L^{-1}), creeks (377 ± 88 L^{-1}), and rivers (359 ± 106 L^{-1}) [51]. The melting waters released by glaciers and snow are mechanisms by which MPs enter the freshwater environment that eventually contaminate seawater systems.

MPs were also detected in the atmosphere. A recent study uncovered the presence of MPs at an elevation of 1425 m above sea level, amidst the Pyrenees mountains in southwestern France [52]. They revealed a total daily estimate of 365 ± 69 MP fragments, films, and fibers deposited (items m^{-2}). These surveys provide evidence that MPs can be found in the most remote and elevated areas and suggest atmospheric transport as the primary mechanism for their disposition.

Many recent investigations have documented the distribution of plastics and MPs in the hydrosphere; waters and sediments of several seas and oceans, providing a snapshot of the level of contamination. A study conducted in the Eastern Mediterranean Sea covering open waters, coastal waters, and enclosed gulfs (Corfu and Saronikos) revealed MP concentrations ranging from 0.012 to 1.62 items m^{-2} (average \pm SD: 0.26 ± 0.36 ; 1.18 ± 1.27 items m^{-3}) [53]. In coral reef systems of the South China Sea (13 islands and reefs in the Xisha Islands) another study reported average sediment concentrations of MPs and small MPs (<100 μm) of 682 ± 780 items kg^{-1} and 375 ± 638 items kg^{-1} , respectively [54]. MPs have also been found contaminating the Nordic Sea, the Beaufort Sea, the Chukchi Sea, the Bering Sea, the East Asian Sea areas, and the Arctic Central Basin ranging from 0.48 to 7.62 MPs m^{-3} (average abundance = 2.91 ± 1.93 items m^{-3}) [55]. Such studies have led to an estimation of 24.4 trillion pieces of MPs in the world's oceans; Fig. 2 illustrates MPs surveys undertaken between 2019 and 2024 across the globe [50–68]. Yet, due to methodological challenges in conducting MP field surveys, the true extent of MPs presence, particularly within subsurface layers, the water column and bottom sediments, remains largely underexplored. As a consequence, the true abundance of

MPs in the ocean is likely to largely exceed these initial estimates [56, 60].

3.2. Impact on marine ecosystems

While the prevalence of MPs in the oceans and their negative impact to marine organisms are now understood, further research is needed to grasp the mechanisms and full extent of the harm these materials inflict. Fig. 3 illustrates the different pathways through which plastics/MPs can have significant biological impacts on the marine ecosystem.

Multiple studies have investigated MP intake by fish and concluded that plastic debris was found in almost all samples from all oceans [69–71]. Furthermore, the impact of MPs on fish were assessed and categorized into two distinct types: mechanical/physical obstruction and chemical damage resulting from intricate toxicity. For example, *Perca fluviatilis* exposed to aged PE MPs demonstrated increased DNA damage and pronounced alterations in the metabolic profiles of fish tissues, triggering heightened stress responses, inflammation, and cellular damage compared to their virgin (non-aged PE) counterparts [72]. The concentrations of MPs were chosen in accordance with environmental concentrations to determine the physiological effects induced by MPs at realistic conditions.

Studies also revealed that exposure to MPs disrupts the gut microbiome and alters the gene expression in sea turtles, resulting in immune system disturbances as well as heightening their vulnerability to opportunistic pathogens [73]. In the USA, an experiment on aquarium-based delphinids (*Tursiops truncatus* and *Orcinus orca*), considering variables such as sex, age, and reproductive stage, found that contaminants caused disruptive effects to their endocrine system and metabolism [74]. Furthermore, phthalates were observed in newborn delphinids, indicating transmission via placenta and/or lactation.

The toxic effects of bisphenol A (BPA) leachate from PS MPs were also observed on the hard coral *Pocillopora damicornis* causing a reduction in photosynthetic yield and tissue composition, yet no such effects were observed on *Dipsastraea pallida* massive corals indicating that the effects of MPs could be species-specific [75]. There are numerous other recent studies that have reported adverse effects to marine life ranging from mild difficulties in swimming and coordination or superficial damage to critical organ malfunctions and mortality [76–83].

Many early studies focussed on the physical hazards MPs pose to marine animals once ingested [84], linking these to biological impacts [14]. More recently research has considered the impact of chemical hazards, i.e., from the polymers and the plastic additives [31,32]. MPs have the capacity to adsorb a diverse array of organic and inorganic contaminants. Furthermore, due to their high surface area and the affinity of organic pollutants for the hydrophobic properties of polymers, the concentrations of these environmental chemicals on MPs often reach levels far exceeding those detected in seawater [85,86]. In addition, chemicals from within the plastic can gradually be released into the surrounding marine environment via a process called leaching and, often, these chemicals are harmful.

3.3. Leaching

Leaching refers to the process by which water or another solvent dissolves and disperses soluble substances, like chemicals or minerals, from a material. This natural occurrence often happens when rainwater seeps through the soil, extracting nutrients or pollutants. In the context of MPs, however, leaching refers to the migration of chemical additives from the plastic into water systems, leading to serious environmental contamination [87]. Leaching is categorized into two distinct types: bioleaching and abiotic leaching. Bioleaching, an entirely biotic phenomenon, involves the action of specific living organisms that release enzymes and chemicals, facilitating the dissolution and extraction of materials [88,89]. On the other hand, abiotic leaching is governed

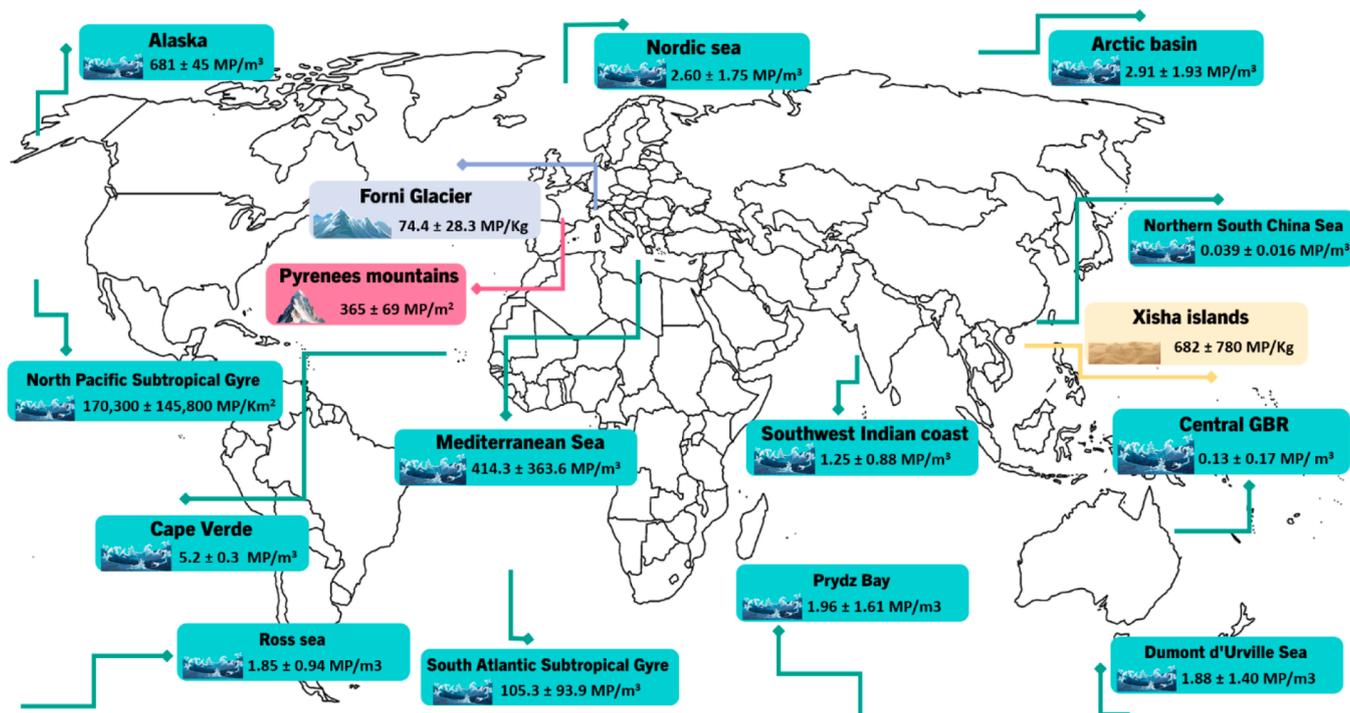


Fig. 2. Recent microplastics counts in different locations across the world [50–68].

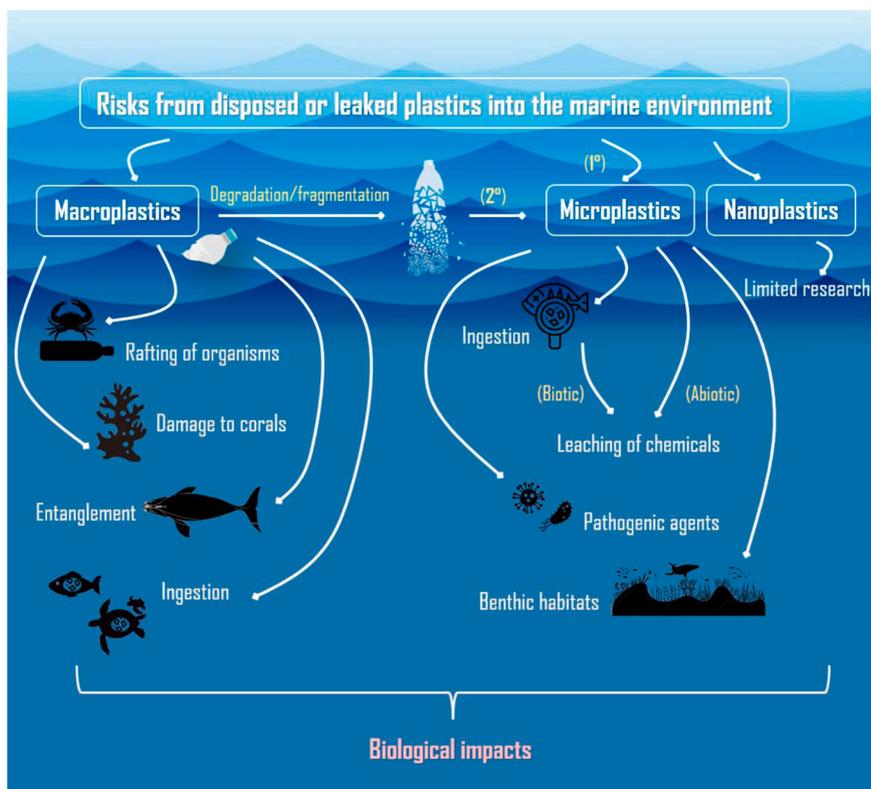


Fig. 3. Graphical overview of the risks of plastic disposal into aquatic systems.

mainly by physical factors such as temperature, UV radiation, wind erosion as well as chemical reactions [90].

Plastic additives incorporated during the plastic manufacturing process enhance the cost-efficiency and optimize the performance of plastic products. Of these, the most commonly used include flame

retardants, plasticizers, and antioxidants, each playing a crucial role in tailoring the characteristics of the final product [91]. Flame retardants are designed to minimize fire risks and slow the combustion process. Among these, brominated flame retardants (BFRs) are the most widely used. The most ubiquitous antioxidant is butylated hydroxytoluene

(BHT) [92–94]. Of the plasticizers, which are mainly used to enhance the flexibility and viscosity of plastics, phthalates - such as DEHP - are the most prevalent, contributing 55 % of global plasticizer sales in 2020. Despite the widespread use of these additives in plastics, they are extremely toxic to marine organisms and pose enduring threats to the aquatic environment [95–97]. For this reason, the leaching of these additives must be prevented or reduced, and to achieve this, leaching mechanisms must first be understood and the behaviors of the chemicals involved thoroughly investigated.

The mechanism of leaching of chemical additives from MPs to aquatic systems can be explained through at least three modalities: diffusion within the plastic matrix, partitioning at the plastic-water interface, and diffusion at the aqueous boundary layer [98,99]. Nonetheless, many other physicochemical and/or environmental factors can affect the leaching of a chemical into the surrounding environment (Fig. 4). A recent comprehensive study into the factors that influence the leaching of the phthalate plasticizer DEHP revealed smaller MPs size, or elevated water temperature, or a lower polymer crystallinity accelerated release of DEHP from the polymer [100]. Conversely, ionic strength was found to inhibit DEHP release from MPs. For example, higher concentrations of Na^+ and Ca^{2+} were found to decrease DEHP release from PLA, PS, and PVC, with the influence of Ca^{2+} being more significant than that of Na^+ . Researchers have also shown that with a decrease in pH the leaching increases [101–104]. Studies on the photodegradation of plastic products have confirmed that UV radiation hastens the weathering process, thereby promoting the release of chemicals into aquatic ecosystems [105,106]. Another recent report indicated that exposure of MPs to agitated seawater increases the leaching of DEHP [107]. The formation of biofilms on MPs was also found to enhance the migration of chemical additives from plastics into the surrounding environment [108].

While studies into the mechanisms of leaching of chemicals from MPs have addressed many knowledge gaps in this area [69,89], there has been comparatively less emphasis on designing plastics with a lower potential for leaching. One solution to the leaching problem lies in the structural modification of chemicals within the polymer, in a way that strengthens their association to the polymer or hinders their release from the matrix [109,110]. Another emerging approach focuses on the development of biodegradable additives and polymers, designed to break down quickly once released into the environment, thereby minimizing harm to aquatic ecosystems [42]. Until a low-cost, broadly effective sustainable polymer-additive system becomes commercially available, the toxicities associated with current plastic usage and existing plastic waste in the environment, along with their profound impacts on marine ecosystems, will need to be managed.

4. Bioplastics

Future plastic products are likely to differ significantly from those used today. The growing demand for more sustainable materials from both societal and environmental pressures have motivated innovation in the plastics industry, leading to the development of novel polymers derived from renewable biological resources that are, in turn, biodegradable. Bioplastics offer an eco-friendly alternative, capable of ready disposal and facile decomposition in the environment, with the help of microbial enzymatic activity, into harmless substances, such as water, carbon dioxide, methane, biomass, and easily eliminable humic matter [111]. Bioplastics offer many advantages compared to traditional fossil fuel-based plastics. Their temporary existence in our environment makes their end-of-life cycle far less costly when compared to the recycling of fossil fuel-based plastics [112–114]. Furthermore, they are made of renewable resources, have a smaller carbon footprint, and require much less energy to be produced.

Bioplastics - until more specific terminology is introduced - is a broad term that includes polymers that are biobased, biodegradable, or both. Even fossil fuel-based polymers that can biodegrade are still considered bioplastics. Based on this definition, not every biobased plastic is biodegradable and not every biodegradable plastic comes from renewable sources. This prompted us to classify bioplastics into three distinct categories (Fig. 5).

4.1. Biodegradable biobased bioplastics

Biodegradability is the metabolic conversion of at least 90 % of material into carbon and energy sources for microbial growth, and is subsequently metabolized into carbon dioxide, mineral salts, water, and new biomass under aerobic conditions, or carbon dioxide, methane, biomass, and/or acids of low molecular weight under anaerobic conditions within 6 months [115]. Accordingly, biobased biodegradable plastics are either derived from biomass, such as plants, polymers sourced from animals, or microbial fermentation by-products.

Plants are the most extensively utilized raw material for producing bioplastics. Vegetable oil, starch, and plant fibers are some of the most prominent sources [32,111]. The most common carbohydrate, starch, is now employed beyond the food and pharmaceutical industries and contributes to about 80 % of the bioplastic market. Corn, potato, rice starch, jackfruit seeds, cassava, sago, and many other starch-containing plants are used in the making of bioplastics such as polylactic acid (PLA), polybutylene succinate (PBS), polyhydroxyalkanoates (PHA) and other starch-based bioplastics. PLA is the most prevalent bioplastic and is widely used in 3D printing [32]. Products such as eating utensils, wrapping equipment, textiles, health care appliances, and transplants are some examples of the widespread usage of starch blends [116]. Cellulose is another naturally occurring polymer that also has glucose as

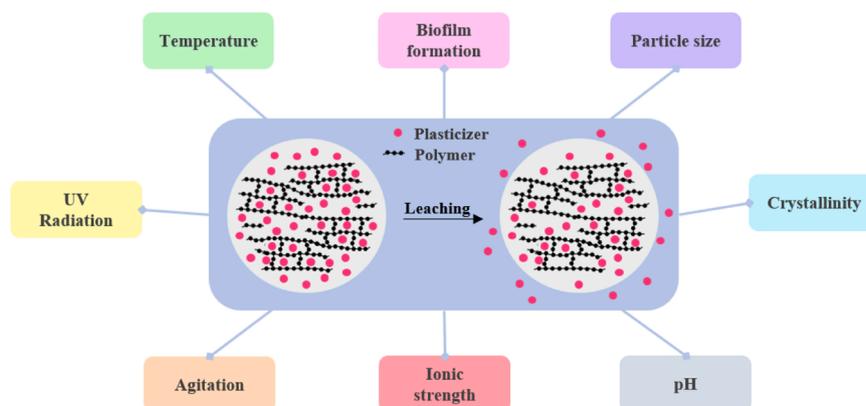


Fig. 4. Graphical overview of the factors affecting leaching of additives from a polymer.

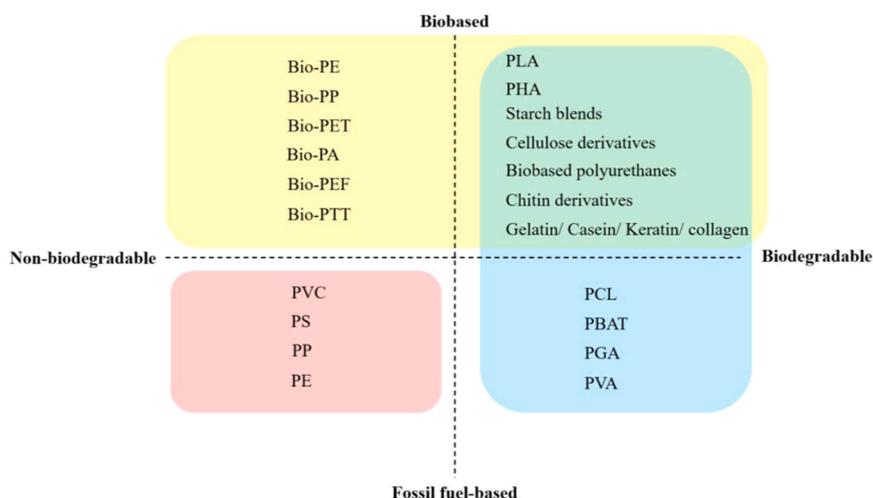


Fig. 5. Graphical overview of the classification of bioplastics.

its monomer. However, the arrangement of glucose in cellulose is different from that in starch giving it a characteristic set of attributes like hydrophilicity, poor solubility, stiffness, strength, and high crystallinity. For this reason, specific symbiotic microbes are needed for its degradation [117]. Cellulose derivatives such as methylcellulose, ethyl cellulose, hydroxy methyl cellulose, hydroxy ethyl cellulose, hydroxypropyl methylcellulose, and carboxymethylcellulose can be found in products such as ophthalmics, toys, sports goods, and spectacle frames [118]. Nonetheless, due to their high production costs, cellulose bioplastics do not feature widely on the market [119]. Vegetable oils like soybean, sunflower, and palm oil are rich in fatty acids, which can be transformed through chemical modification into polyols that serve as the building blocks for polymerization processes, leading to the creation of bioplastics. A notable example is epoxidized soybean oil (ESO), which is frequently utilized in the production of biobased polyurethanes and other polymers. Vegetable oils can also undergo a reaction with alcohols yielding fatty acid methyl esters (biodiesel) that can be polymerized to fabricate advanced bioplastic materials. Vegetable oils are also sometimes blended with other biobased plastics to improve their qualities [120]. Applications for bioplastics made from vegetable oil are; adhesives, packaging, paint and coatings, and biomedicine [121].

Animals also contribute to the realm of biobased and biodegradable materials used in bioplastic production. Among the most abundant biopolymers is chitin, a remarkable substance primarily extracted from the shells of crustaceans such as crabs, prawns, and shrimp. Chitin is also found in the exoskeletons of various arthropods and within the cell walls of certain yeasts and fungi [32]. Chitosan, a non-toxic amino polysaccharide derived from chitin, was estimated to have a market value of USD 6.8 billion in 2019 [122]. Currently, there are various applications for chitosan in biomedicine, biotechnology, healthcare, the food industry, manufacturing, and agrochemicals. Gelatine, found in animal bones, skin, and connective tissue is also used in the making of edible films, food packaging, and recently, in ingestible medical devices [123, 124]. Casein, a protein-based bioplastic obtained from milk, is being used in biodegradable films, coatings, and adhesives due to its ability to form a strong, flexible film [125]. Keratin, collagen, and blood are other protein sources that are used to a lesser extent in the manufacturing of animal-based bioplastics [126].

Microbial fermentation by-products provide sustainable alternatives to plant biomass as these do not compete with feedstocks that are also used as food or feed, which have associated complications [127]. The earliest discovery in this field is poly(3-hydroxybutyrate) (PHB), the most prevalent member of a broader class of optically active microbial polyesters known as polyhydroxyalkanoates (PHA). These biopolymers have garnered significant attention due to their versatility and abundance

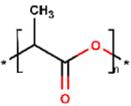
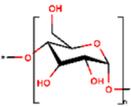
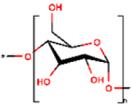
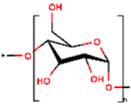
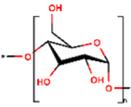
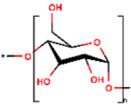
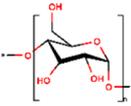
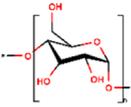
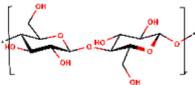
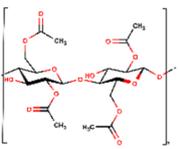
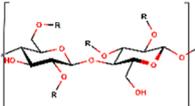
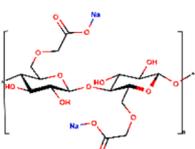
[128]. A diverse range of microorganisms, including bacteria, microalgae, and archaea, produce PHAs as a response to adverse growth conditions. They are energy and carbon storage compounds that can be synthesized from a wide array of renewable substrates, such as rice straw, bagasse, and macroalgae [129–132]. The family of PHAs includes numerous types of biopolymers, such as polyhydroxyvalerate (PHV), polyhydroxybutyrate (PHB), poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), polyhydroxyhexanoate (PHH), poly-4-hydroxybutyrate (P4HB), poly-5-hydrovalerate (P5HV), and poly-3-hydroxypropionate (PHP) according to the variation in their structures which, in turn, influences their properties [133]. These biopolymers currently find use in diverse applications, such as packaging, energy sectors, wastewater treatment, and biomedical applications [134]. However, due to the high costs associated with production and recovery, microbial fermentation is currently only used to a limited extent [135]. Table 1 provides a collective overview of the sources, structures, uses, and sustainability of biodegradable biobased bioplastics in the marine environment.

4.2. Non-biodegradable biobased bioplastics

Non-biodegradable bioplastics are typically derived from renewable resources such as sugarcane, corn, and biomass. Despite their origins, the manufacturing process involves a series of complex transformations (pretreatment, hydrolysis, fermentation, and various organic reactions) that fundamentally alter the chemical composition of these materials, rendering them non-biodegradable. [111]. Nearly half of the biobased bioplastics available on the market fall into this non-biodegradable category. Prominent examples include bio-polyethylene (bio-PE), bio-polyethylene terephthalate (bio-PET), bio-polypropylene (bio-PP), bio-polytrimethylene terephthalate (bio-PTT), bio-polyethylene furanoate (bio-PEF), and bio-polyamide (bio-PA). Currently, these feature in materials applications across sectors like biomedicine, cosmetics, automotive, personal care, aerospace, packaging, air/water filtration and toys [155–160]. In 2023, bio-PA, bio-PTT, and bio-PE were the most used in Europe with market shares of 18.3 %, 13.5 %, and 12.3 %, respectively [161]. Table 2 provides a collective overview of the sources, structures, uses, and sustainability of non-biodegradable biobased bioplastics in the marine environment.

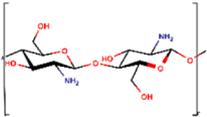
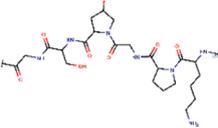
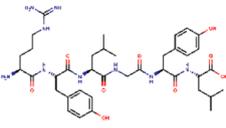
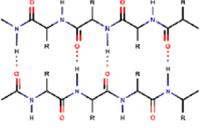
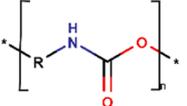
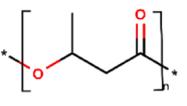
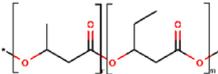
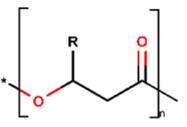
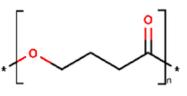
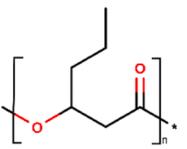
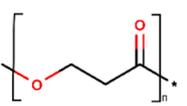
Given the chemical resemblance between biobased polymers and their petroleum-based counterparts, their environmental impact in landfills is comparably detrimental. Therefore, waste from these materials should be managed with the same rigor as traditional plastics. To address this challenge, advanced laboratory techniques such as pyrolysis and gasification must be developed and refined for large-scale industrial applications. Additionally, there is a pressing need to raise awareness

Table 1
Collective overview of biodegradable biobased bioplastics and their sources, structures, uses, and their sustainability in the marine environment.

Polymer	Source	Structure	Uses	Biobased	Biodegradability in marine conditions	Reference
Poly(lactic acid) (PLA)	Lactic acid from fermented starch, sugar crops, and whey		3D printing, biodegradable medical devices, and plastic films	Yes	Low molecular weight PLA is biodegradable in marine conditions	[136]
Cassava starch	Cassava		Packaging	Yes	Biodegradable in water	[137]
Jackfruit seed starch	Jackfruit		Packaging, edible films, and coatings	yes	Biodegradable in water	[138]
Mango seed starch	Mango		Packaging	Yes	Biodegradable in water	[139]
Corn starch	Corn		Packaging and agricultural films	Yes	Biodegradable in water	[140]
Rice starch	Rice		Packaging	Yes	Biodegradable in water	[141]
Potato starch	Potato		Packaging	Yes	Biodegradable in water	[140]
Banana peel starch	Banana		Packaging and carrying bags	yes	Biodegradable in water	[142]
Bacterial cellulose (BC)	Bacteria such as: <i>Acetobacterxylinum</i>		Antimicrobial filters, pollution biosensors, and sustainable energy equipment	Yes	Biodegradable in water	[143]
Cellulose acetate	Cellulose from wood, fibres, cotton, bamboo, and recycled paper		Textile, optoelectronic film, anti-fog eyewear, LCD, and coating	Yes	Biodegradable in water	[143]
Methyl cellulose, ethyl cellulose, hydroxy methyl cellulose, hydroxy ethyl cellulose	Cellulose from wood, fibres, cotton, bamboo, and recycled paper		Construction, printing, film fabric, sealants, and battery packs	Yes	Biodegradable in water	[143]
Carboxymethyl cellulose (CMC)	Cellulose from wood, fibres, cotton, bamboo, and recycled paper		Cosmetics, paper, paint, and pharmaceuticals	Yes	Biodegradable in water	[143]

(continued on next page)

Table 1 (continued)

Polymer	Source	Structure	Uses	Biobased	Biodegradability in marine conditions	Reference
Chitosan	Chitin from crustaceans' shells and exoskeleton of arthropods		Biomedicine, biotechnology, healthcare, the food industry, manufacturing, and agrochemicals	Yes	Biodegradable in water	[144]
Gelatin	Animal connective tissue, bones and skin		Skin care products, coatings, packaging, edible films, and medical uses	Yes	Biodegradable in water	[145]
Casein	Dairy products		Films, coatings, and adhesives	Yes	Biodegradable in water	[146]
Keratin	Hair, animal skin, nails, hooves, horns, and feathers		Textile, agriculture, medical products, cutlry, and packaging	Yes	Biodegradable in water	[147]
Biobased polyurethane	Vegetable oil, sugar cane, and other plants		Coatings, adhesives, packaging, sealants, construction, textile, toys, and medical uses	Yes	Biodegradable in water	[148]
Polyhydroxybutyrate (PHB)	Microbial fermentation		Packaging, energy sectors, wastewater treatment, and biomedical applications	Yes	Slow biodegradation in water	[149]
Poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV)	Microbial fermentation		Packaging, energy sectors, wastewater treatment, and biomedical applications	Yes	Biodegradable in water	[150]
Polyhydroxyalkanoate (PHA)	Microbial fermentation		Drug delivery systems, packaging, coatings, 3D printing, tissue engineering, and textile	Yes	Biodegradable in water	[151]
Poly(4-Hydroxybutyrate) (P4HB)	Microbial fermentation		Medical applications	Yes	Biodegradable in water	[152]
Polyhydroxyhexanoate (PHH)	Microbial fermentation		Packaging, energy sectors, wastewater treatment, and biomedical applications	Yes	Biodegradable in water	[153]
Poly-3-hydroxypropionate (PHP)	Microbial fermentation		Packaging, energy sectors, wastewater treatment, and biomedical applications	Yes	Biodegradable in water	[154]

about the environmental hazards posed by bioplastic waste. The prevailing enthusiasm for bioplastics may lead consumers to dispose of these products improperly, favoring unsuitable locations over designated waste management facilities [162,163].

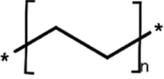
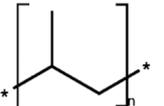
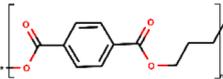
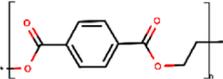
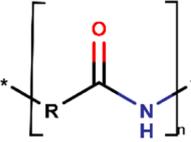
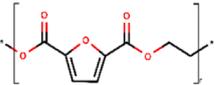
4.3. Biodegradable non-biobased bioplastics

Non-renewable resources are also used to produce biodegradable plastics. This means that biodegradability could be influenced by

characteristics such as molecular weight, elasticity, and chain properties and does not necessarily depend on the starting material being from a biobased source. For example, poly-caprolactone (PCL) which is a fossil fuel-based plastic, completely degrades within 6 weeks in compost conditions [166]. Due to the mechanical and gradual degradation properties of PCL, it is mostly employed in healthcare applications, such as long-term implants, drug delivery systems, and tissue engineering [167,168]. Another important fossil fuel-based bioplastic - polybutylene adipate terephthalate (PBAT) - is mainly used in good quality packaging

Table 2

Collective overview of non-biodegradable biobased bioplastics and their sources, structures, uses, and their sustainability in the marine environment.

Polymer	Source	Structure	Uses	Biobased	Biodegradability in marine conditions	Reference
Polyethylene (Bio-PE)	Biobased ethylene from renewable biomass such as: corn, sugarcane, and algae		Packaging, medical products, construction, textile, agriculture, toys	Yes	Does not biodegrade in water	[159]
Polypropylene (Bio-PP)	Biobased propylene from renewable biomass such as: corn, sugarcane, and algae		Packaging, consumer goods, automotive, and construction	Yes	Does not biodegrade in water	[160]
Polytrimethylene terephthalate (Bio-PIT)	Biobased propanediol (PDO) and biobased terephthalic acid (TPA) from renewable biomass		Engineering materials such as fibers and film material.	Yes	Does not biodegrade in water	[156]
Polyethylene terephthalate (Bio-PET)	Biobased ethylene glycol and biobased terephthalic acid (TPA) from renewable biomass		Packaging, and recyclable bottles	Yes	Does not biodegrade in water	[158]
Polyamide (Bio-PA)	Biobased caprolactam from biomass such as: castor oil and sugarcane, and biobased adipic acid from carbohydrates		Electronics, construction, consumer goods, textile, medical devices	Yes	Does not biodegrade in water	[164]
Polyethylene furanoate (Bio-PEF)	Biobased furan-2,5-dicarboxylic acid from biomass such as: sugar cane, corn, and cellulose and biobased ethylene glycol from fermented sugarcane or corn		Consumer goods, packaging, textile, medical materials, and electronics	Yes	Does not biodegrade in water	[165]

owing to its biocompatibility, flexibility, and cheap processing costs [169]. A previously mentioned bioplastic – PBS – is originally a biodegradable fossil fuel-based bioplastic, however, it is usually modified through the addition of starch to the blend making it biobased. PBS is utilized in food and cosmetics preservation [170]. Polyglycolic acid (PGA) and polyvinyl alcohol (PVA) – which is a water-soluble bioplastic – are other examples that are currently being used to a lesser extent [171–173]. Table 3 provides a collective overview of their sources,

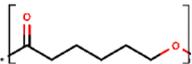
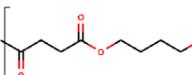
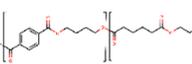
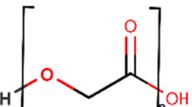
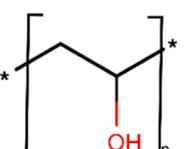
structures, uses, and their sustainability in the marine environment.

References [179–181] also provide comprehensive reviews of the biodegradation and decomposition times of many important bioplastics in marine environments.

For the first time, and with actual production data at hand, a comparative analysis of production capacities and actual output in 2023 revealed that the bioplastics industry is operating at nearly full throttle, with an average utilization rate of 82 %. Fig. 6 shows the percentages of

Table 3

Collective overview of biodegradable non-biobased bioplastics and their sources, structures, uses, and their sustainability in the marine environment.

Polymer	Source	Structure	Uses	Biobased	Biodegradability in marine conditions	Reference
Polycaprolactone (PCL)	petrochemical feedstocks		Packaging, implant, and drug delivery	No	Biodegradable in water	[174]
Polybutylene succinate (PBS)	Butanediol mostly from petrochemical feedstocks		3D printing, packaging, consumer goods, textile, agriculture, and medical devices	No	Slow biodegradation in water	[175]
Polybutylene adipate terephthalate (PBAT)	Mostly petrochemical adipic acid and terephthalic acid		Packaging, consumer goods, textile, agriculture, and medical devices	No	Slow biodegradation in water	[176]
Poly(glycolic acid) (PGA)	Glycolic acid from petrochemical feedstocks		Shape memory films, packaging, antibacterial coatings and biomedical applications	No	Biodegradable in water	[177]
Polyvinyl alcohol (PVA)	Polyvinyl acetate from petrochemical feedstocks		Laundry detergents, packaging, adhesives, coatings, medical devices and textile	No	Biodegradable in water	[178]

the bioplastics that are currently being produced [161]. This industry performance is driven by rising demand and the need for increasingly sophisticated products. Packaging commands the largest market share, comprising 43 % of the total bioplastics market in 2023. Looking ahead, global bioplastics production capacity is set for a remarkable expansion, expected to rise from approximately 2.18 million tons in 2023 to an estimated 7.43 million tons by 2028 [161].

Although bioplastics are designed to be non-toxic and biodegradable, they continue to be a subject of controversy concerning their environmental impact. For example, some bioplastics can only degrade in active landfills under specific conditions, which indicates that without guidance, their accumulation due to improper disposal and management is still possible [179]. Moreover, bioplastic production was found to generate more pollutants when compared to traditional plastics due to the chemicals needed in the treatment of crops (e.g., pesticides and fertilizers) and those needed in the polymerization of plastics from organic materials [182]. On the other hand, bioplastics don't completely disappear when they biodegrade but fragment into MPs instead, accelerating the spread of debris in our oceans, absorbing more toxins and dispersing them further [183,184]. They also retain the potential to leach harmful and toxic chemical additives embedded within the plastic polymer, most crucially plasticizers [34,185,186]. Therefore, researchers are focusing on developing more sustainable plasticizers either through structural modifications that strengthen their association to the polymer and hinders their release from the matrix [98,99], or ensuring their safe and rapid degradation once released into the environment, thereby minimizing harm to aquatic ecosystems [31].

5. Plasticizers

Plasticizers are the most essential additives to plastic materials. In 2023, the plasticizer market was valued at USD 17.98 billion. Expected growth from USD 19.2 billion in 2024 to USD 28.45 billion by 2032 is forecasted, which translates to an annual growth rate of 5.17 %. The phthalates plasticizer sector held the largest share of the market in 2022, however, the rising tide of consumer awareness and regulatory frameworks such as the Registration, Evaluation, and Authorization of Chemicals (REACH) regulations (REACH Annex XVII Entry 51), are shifting the focus toward less harmful non-phthalate alternatives [187, 188]. Consequently, scientists are researching new strategies to mitigate the hazards caused by current plasticizers to the environment. The goal is to either create plasticizers from green renewable materials that are also safe and inexpensive, without adversely affecting performance, or to prevent leaching of plasticizers from polymers altogether. So far,

many promising techniques have emerged that could improve their toxicity, mitigation, and overall sustainability. A plasticizer with such properties will be especially beneficial for marine environments as they are the most compromised by the presence of these chemicals (Figs. 7–12).

5.1. Strategies

5.1.1. Hyper-branched polyesters

One effective strategy for developing a sustainable plasticizer involves limiting its migration from the polymer matrix as seen in plasticizers made of hyperbranched polyesters. The idea is to increase the compatibility with the matrix by adding many terminal functional groups, increasing their polarity and dispersibility, and lowering their volatility and diffusion rate. Hyperbranched polyesters have been developed from biobased materials such as tung oil, castor oil, and cashew shell oil, and the results revealed improved leaching properties, transmittance, and overall better plasticization when compared to dioctyl phthalate (DOP) [189–191]. Other renewable resources used in the preparation of hyperbranched polyesters as plasticizers include soybean oil and multifunctional acids such as oleic acid, adipic acid, and citric acid [192–194]. Hyperbranched polyester plasticizers were also prepared from petroleum sources that are of low toxicities such as glycerol and poly-(caprolactone) and showed very stable migration rates [39,195,196].

5.1.2. Micro/nanofillers

More modern methods are being investigated to reduce the leaching of plasticizers to the surrounding environment such as adding micro/nano-fillers to the plasticizer. Nano-fillers provide dual benefits through the mechanisms of tortuosity and adsorption. Nano-fillers compel plasticizer molecules to traverse a more complex route before escaping the material. They also have extensive surface area and many interactive groups that encourage the adsorption of plasticizer molecules onto filler surfaces. Both mechanisms make it very hard for plasticizers to leach out of the polymer matrix and, in turn, improve its sustainability. The addition of natural nanofibrils such as chitin nanofibers to PLA/PBS blends with acetyl *n*-tributyl citrate (ATBC) as a plasticizer was examined. Migration tests revealed that the presence of chitin nanofibrils significantly slowed down the rate of plasticizer migration [197]. In another study, nano-CaCO₃ was used as filler and added to the plasticizer poly(1,2-propylene glycol adipate) (PPA) in PVC sheets to assess restraining ability on DOP migration rates. This approach was effective in suppressing the leaching of DOP in the PVC

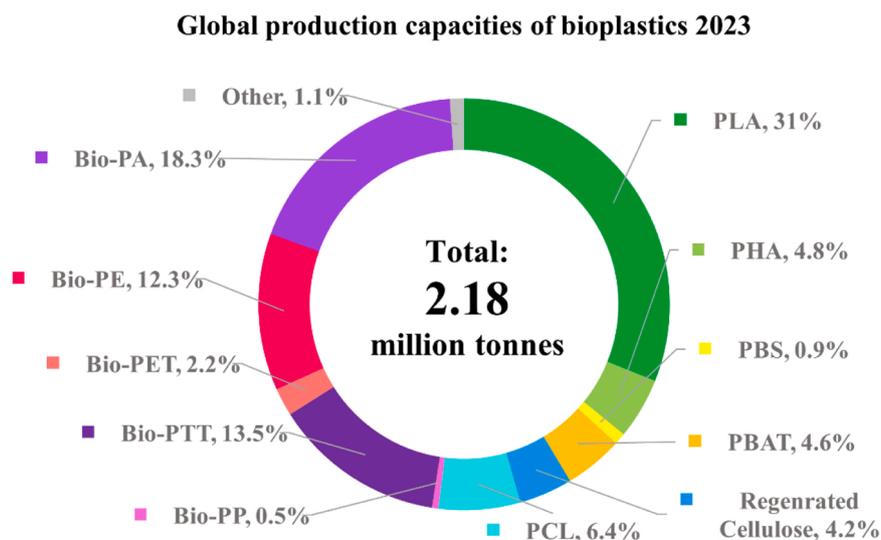


Fig. 6. Chart illustrating the production capacities of bioplastics in 2023 across the globe [123].

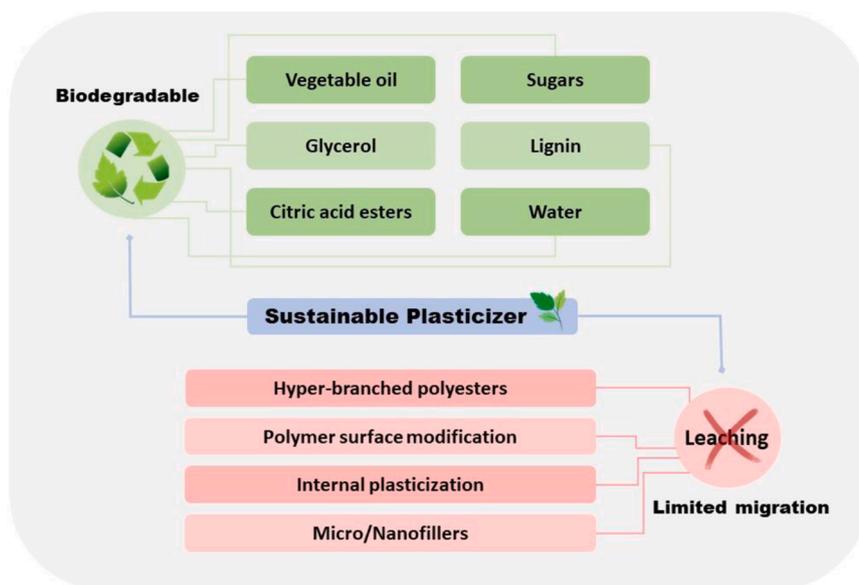
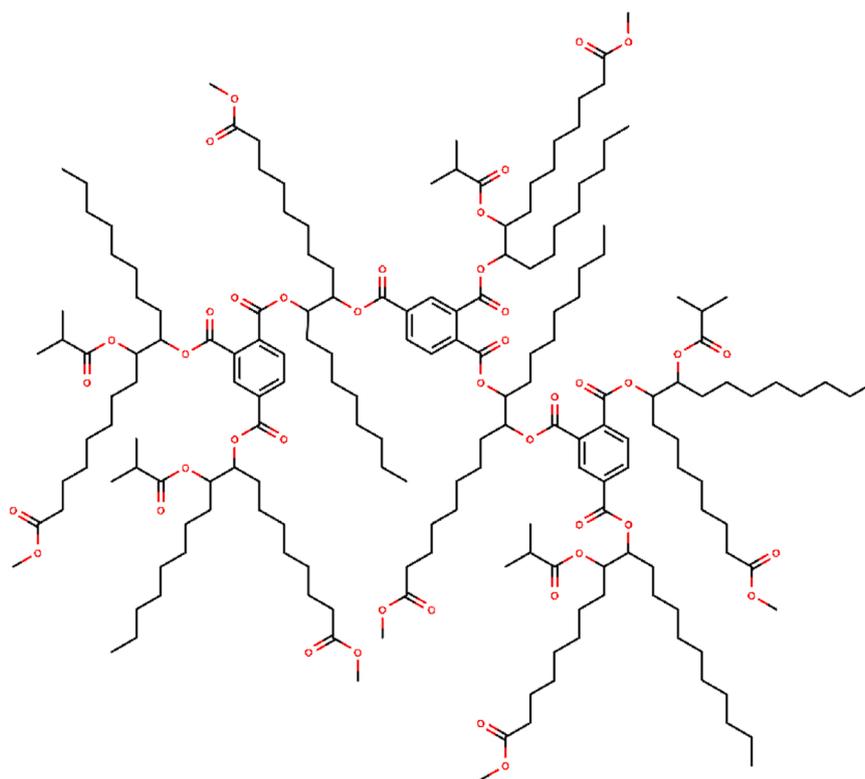


Fig. 7. Graphical overview of multiple strategies to obtain a sustainable plasticizer.



Oleic acid-derived hyperbranched polyester

Fig. 8. Example of a hyperbranched polyester derived from oleic acid as a plasticizer [167].

matrix [198]. Single-walled carbon nanotubes (SWCNTs), organoclay, TiO_2 , as well as ZnO nanoparticles were also tested as fillers in PVC composites, and their influence on plasticizer migration was measured. Results highlighted the efficiency of those nanofillers in hindering the migration of the plasticizer and revealed that carbon nanotubes served as the best nanofiller for migration prevention of those screened [199].

5.1.3. Polymer surface modification

Polymer surface modification offers a different path to limiting plasticizer leaching. There are multiple techniques available for the modification of the surface of a polymer. In this regard, surface coating and surface cross-linking are among the most important methods.

Coating the surface prevents plasticizer leaching and protects the polymer against UV degradation. Coating the surface of PVC with a sol-

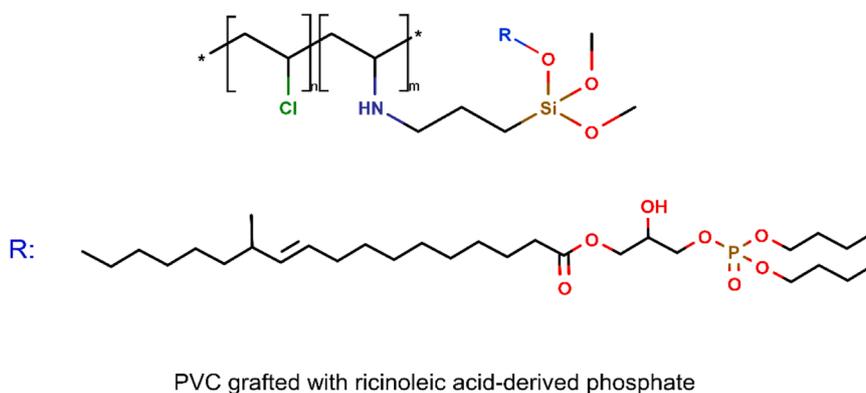


Fig. 9. Polyvinyl chloride (PVC) grafted with ricinoleic acid-derived phosphate as internal plasticizer [186].

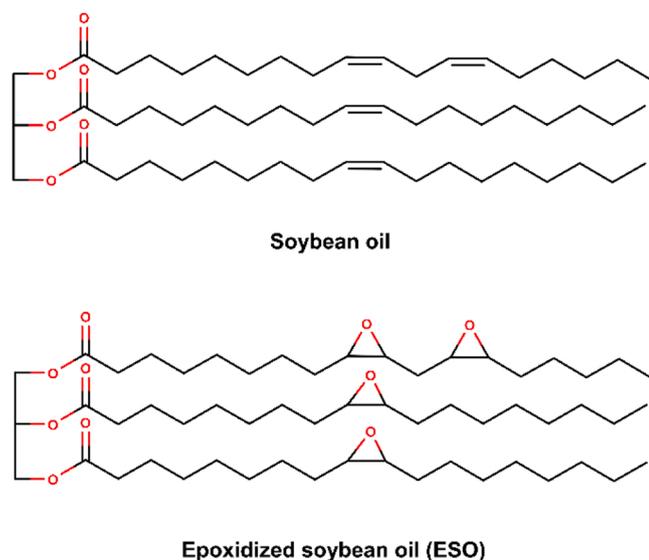


Fig. 10. Chemical structure of soybean oil and epoxidized soybean oil (ESO).

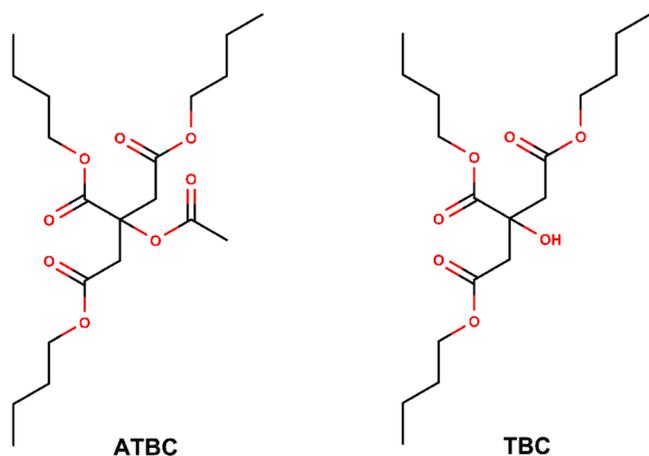


Fig. 11. Structures of Acetyl tributyl citrate (ATBC) and tributyl citrate (TBC).

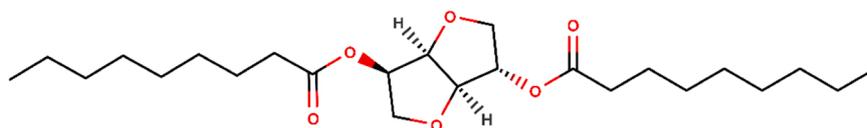
gel hybrid layer based on two organic functionalized titanium alkoxides (methacryloxy propyl grafted silicon alkoxide and a titanium IV isopropoxide chelated with acrylic acid mixed with a photoinitiator (2,2-dimethoxy-1,2-diphenylethan-1-one) has prevented plasticizer migration and afforded up to 98 % protection to PVC against UV degradation [200]. Amyloid-like aggregates were also used as a coating in migration

prevention and returned excellent results [201]. Another recent study coated PVC catheters with thermoplastic polyurethane, the coating proving effective against plasticizer migration [202]. More coating materials such as titanium, heparin, and cyclodextrin derivatives have been tested and provided promising results, however, the application of these methods remains limited as they are not a cheap option and do not always provide optimal results [203–207]. More experimentation and research into surface coatings are required if they are to become a viable technique in leaching prevention.

Surface cross-linking is another successful method to prevent plasticizer leaching from a polymer matrix. Crosslinking the polymer chains with covalent or non-covalent bonds through physical treatments such as plasma or γ -irradiation, or through chemical treatment, can provide a surface that acts as an obstacle hindering the migration of plasticizers. A recent study that modified medical-grade PVC surfaces by brief dip-coating and then light illumination using zwitterionic carboxybetaine and photosensitive cross-linking particles proved effective and prevented the leaching of the plasticizer out of the polymer [208]. The leaching of tributyl acetyl citrate (TBAC) from PVC into water was tested after applying oxygen and argon plasma treatment to modify the polymer surface structure. Oxygen plasma treatment was found more effective than the latter, however, more research into this method is required to progress its application [209]. In another study, PVC sheets were modified with UV irradiation after coating with poly(azido acrylate)s in a dichloromethane solution to increase crosslinking of the PVC surface layer and found to have much better migration prevention than unmodified PVC sheets [210]. Many other chemical and physical methods have been investigated, however, many have been found to be more harmful than useful, e.g., chemical treatment with thiosulphate [211]. Thus, many issues remain unaddressed, and advancements in these techniques remains a work in progress.

5.1.4. Internal plasticization

Internal plasticization occurs when the plasticizer is covalently bound to the polymer matrix to prevent it from leaching. Grafting PVC with ricinoleic acid-derived phosphate ester as an internal plasticizer has proven to be an excellent anti-migration method due to the formation of covalent bonds between PVC and the plasticizer [212]. Soybean oil, cardanol glycidyl ether, and epoxidized acetylated castor oil methyl ester have each been examined as internal plasticizers and grafted onto PVC, with leaching tests showing no migration in hexane [213]. Recently, internally plasticized PVC was prepared using a branched plasticizer based on eugenol, a sustainable biobased material that is itself an effective plasticizer retained within the polymer [214]. Similarly, the application of the Mannich base of recycled waste cooking oil methyl ester as an internal PVC plasticizer has resulted in migration prevention [215,216]. Limited leaching from PVC has been achieved with a simple one-pot method using the cheap raw material trichlorotriazine [217]. PVC has also been internally plasticized by displacing chlorine with



Isosorbide di-nonanoate

Fig. 12. Structure of isosorbide derivative as a plasticizer.

phthalate-based thiol additives which completely stopped the migration of the plasticizer [218]. The biobased epoxy *p*-phenylenedioleic acid ester internal plasticizer was also tested with PVC and found to reduce the migration rate [219].

5.1.5. Biobased biodegradable plasticizers

The prospect of a future built on entirely biodegradable biobased materials is becoming increasingly attainable. Experiments have been conducted on various materials derived from renewable resources with many showing promise as plasticizers. Water is one of the safest and most renewable resources in existence and its application as a plasticizer has been widely reported in the literature [220]. Water was found to reduce glass transition temperature (T_g) values of hydrophilic polymers, such as starch and proteins, as well as providing synergistic effects to biobased additives in hydrophobic polymers [221,222].

Despite glycerol being a petroleum-based chemical, it is regarded as a safe and cheap material, and its production is in fact, preferable [223]. Glycerol is the second most common plasticizer after water and has been extensively utilized in different combinations of biobased and biodegradable plasticizers. Some of the most recent applications of glycerol as a plasticizer include bacterial cellulose-based composites, sodium conducting biopolymer blends, thermoplastic starch, and preparation of organic carbonate plasticizers [224–227].

Vegetable oil is a desirable plasticizer with the advantages of being environmentally friendly, cheap, non-toxic, biobased, and biodegradable [220]. They are composed of esters of glycerol and various fatty acids. The presence of unsaturated chains in these structures allows fatty acids to intercalate between the polymer chains, enhancing their mobility. Additionally, they can form bonds with the polymer matrix that can improve their compatibility and limit their migration [220]. The most common fatty acids from vegetable oils that are currently being used as plasticizers are oleic, linoleic, and linolenic acids [228–231]. Soybean oil is one of the most widely tested vegetable oils and is currently being used as a plasticizer with impressive results [232, 233]. Sunflower, cashew nutshell, palm, jojoba, cotton seed, and olive oils also have great potential as biobased plasticizers [234–239].

Another advantage in using fatty acids as plasticizers is their ability to be epoxidized (via the alkene groups) and esterified (via the carboxylic acid groups), both reactions that can improve their performance. The epoxy group in epoxidized plasticizers allows for the neutralization and scavenging of HCl released by PVC during degradation [240]. They also limit leaching out of the polymer matrix by enhancing interactions with the polymer chain. Epoxidized soybean oil is the first epoxidized vegetable oil currently utilized as a biobased plasticizer and represents an alternative to traditional phthalates in biopolymers such as PLA and PBS [240–243]. The effectiveness of epoxidized palm oil as a PLA plasticizer was demonstrated, while epoxidized castor oil greatly improves the properties of PVC [42,244,245]. Furthermore, epoxidized olive oil, epoxidized linseed oil, epoxidized waste cooking oil, and epoxidized canola oil have been examined as potential modern plasticizers [246–250]. Other oils, such as tung oil (woody oil) and eugenol (clove oil), were modified and tested with PVC and have displayed enhanced properties yielding promising results as plasticizers [251, 252].

Citric acid esters can be obtained from orange waste and have been heavily investigated as plasticizers. Acetyl tributyl citrate (ATBC) and

tributyl citrate (TBC) are industrialized due to their outstanding performance as biobased plasticizers. They have impressive flexibility at low temperatures, good water and light resistance, and high thermal stability [253–255].

Sugars such as glucose and mannose can be modified to produce alcohols and isosorbide. Starch-containing crops such as rice, corn, potatoes, and wheat are common sources of these sugars. Isosorbide derivatives have proven to be good biobased plasticizers and are replacing phthalates in many industries [256–258]. Glucose, furan esters, and sucrose are other sugars being investigated for their potential as plasticizers [42,259–261].

Lignin has been investigated as a potential source of biobased plasticizers. Vanillic acids from vanillin (lignin component) as plasticizers are becoming a hot research topic. Vanillic acid esters, obtained via a simple two-step reaction, have delivered improved PVC properties while being non-toxic even at high concentrations [262]. Lignosulfonates were also produced from kraft lignin (a product of the pulping process) and are being investigated as potential plasticizers [263].

Plasticizers are essential additives in the plastic industry, but their current formulations are highly toxic to marine life, which arguably suffers the most from plastic waste pollution. Following the prohibition of several phthalate plasticizers, various emerging and alternative plasticizers have entered the market and while their plasticizing properties and biodegradability have been assessed, a significant knowledge gap regarding their toxicological profiles still remains [264].

6. Conclusion

The adverse effects plastics cause to marine life may become irreversible if current practices continue, especially given the rapid rate of plastic production and its entry into aquatic ecosystems. Nonetheless, the transition to biobased materials as replacements for petroleum-based plastics is achievable in the near future. The most promising bioplastics are those derived from renewable, biobased materials that are also capable of biodegradation, such as PLA, PHA, and PBS, along with starch and cellulose-based plastics. Other biobased plastics like bio-PE and bio-PP remain non-biodegradable and although plastics like PCL and PBAT are biodegradable, they are still sourced from non-renewable resources.

Therefore, the journey towards a bioplastic future faces many obstacles and dilemmas, including the potential risk of merely shifting one set of negative impacts to another [32,265,266]. In the current state, studies show that biodegradable plastics do not completely biodegrade but turn into microparticles instead, accelerating the spread of debris in our oceans, absorbing more toxins and dispersing them further [183, 184]. These microparticles may or may not degrade in the environment as we still have little evidence of their consequences and limited studies about their effect on living organisms [267]. Additionally, bioplastics are mainly dependent on essential food crops such as corn, sugarcane, and potatoes. Over-reliance on a limited range of feedstocks makes the supply chain susceptible to vulnerabilities.

Consequently, regulatory policy frameworks have been created by the European Union to guide citizens, public authorities and economic operators towards a better understanding of biodegradable plastics and their impact on the environment [268]. Additionally, ISO 14040 and EN 16760 regulatory standards were introduced internationally to act as a

guideline for life cycle assessments (LCAs) for biodegradable plastics [28]. The United Nations Environment Programme (UNEP) is also working closely to the UN system to raise awareness towards plastic pollution, highlighting the necessity for science and policy to collaborate in order to achieve the SDGs and to transition to a more sustainable future.

Future research should focus on innovative feedstock sources, including waste materials, agricultural by-products, and non-edible crops, to produce bioplastics. On the other hand, the development of biobased plasticizers - such as epoxidized vegetable oils, citric acid esters and isosorbides - which are non-toxic to marine organisms and capable of rapid degradation, has shifted from a mere luxury to a necessity. To mitigate environmental harm, it is imperative these eco-friendly alternatives replace traditional, non-renewable plasticizers like phthalates. Finally, substantial effort must be dedicated to understanding the relationship between the biological toxicity and chemical structure of biobased plasticizers, as comprehensive toxicological data on these substances are currently limited.

Environmental implication

This review takes a holistic approach to discussing microplastic pollution, with a focus on microplastics and associated chemical additives (e.g., phthalates) that disrupt the health of marine ecosystems. As these chemical contaminants are ingested by marine organisms, subsequently entering the food chain, the review also examines sustainable solutions proposed to date. This review incorporates published research from the *Journal of Hazardous Materials*, covering topics such as microplastic quantification, additive toxicity, plastic biodegradation, and their effects on marine animals and humans. The exploration of these topics within the review underscores its relevance and suitability for the *Journal of Hazardous Materials*.

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Motti Cherie A.: Writing – review & editing, Supervision, Conceptualization. **Vamvounis George:** Writing – review & editing, Supervision, Conceptualization. **Ghobish Sarah A.:** Writing – review & editing, Writing – original draft, Conceptualization. **Bissember Alex C.:** Writing – review & editing, Supervision.

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During the preparation of this work the author(s) used ChatGPT to occasionally check grammar. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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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.

Data availability

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

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