Journal of Hazardous Materials

Are biodegradable plastics an environmental rip off?

--Manuscript Draft--

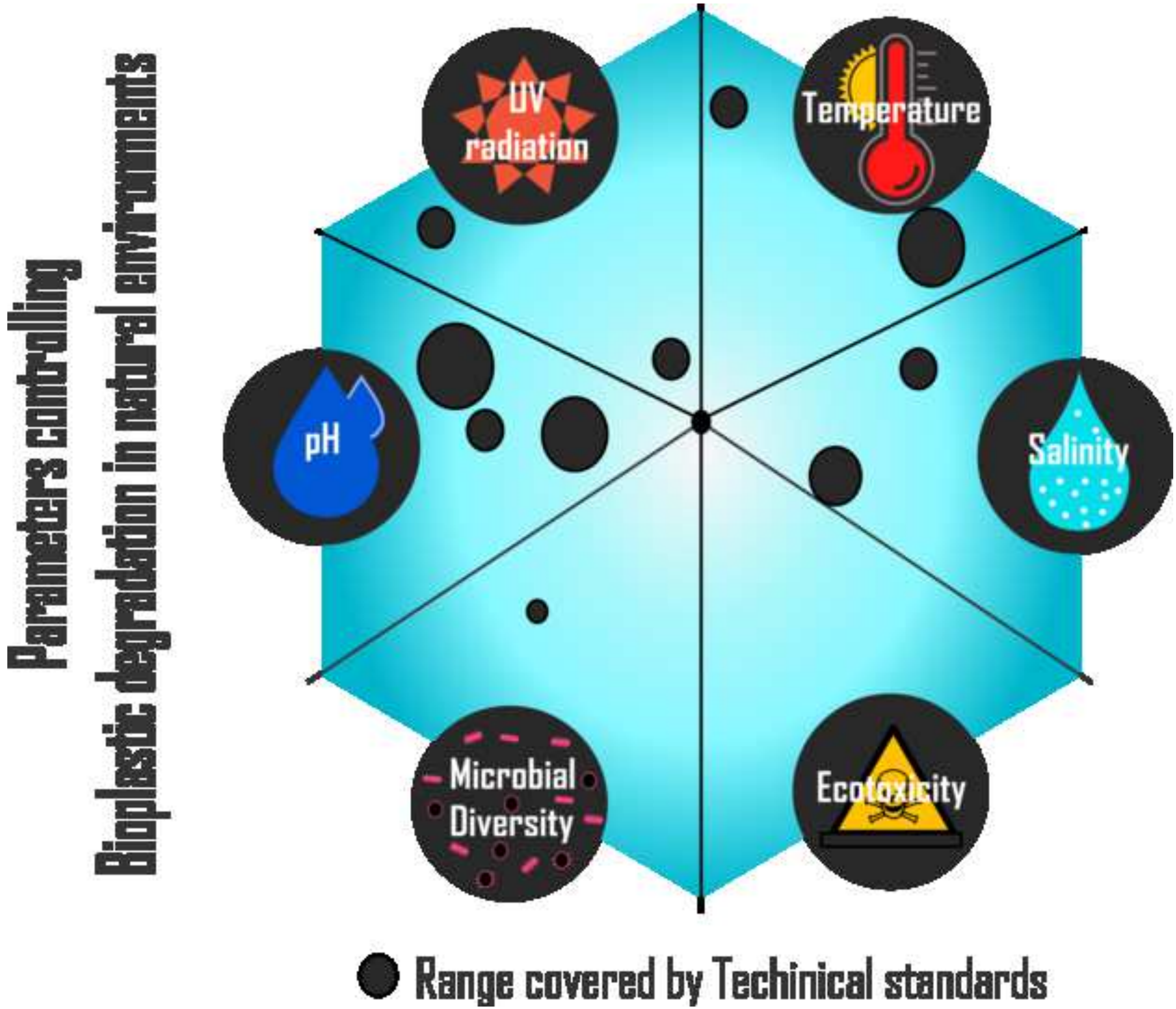
Manuscript Number:	HAZMAT-D-21-01752
Article Type:	Research Paper
Keywords:	bioplastic; technical standards; pollution; marine debris; contamination
Abstract:	While the use of supposedly biodegradable polymers has been recognized as a global strategy to minimize plastic pollution, the technical standards (TS) used to attest biodegradability of alternative polymers may not be in compliance with most environmental parameters observed in marine and coastal ecosystems worldwide. Indeed, through a careful assessment of the TS currently in use, this study evidenced that these guidelines cover only a fraction of the diversity of biogeochemical parameters seen in nature and largely disregard the deep-sea. Thus, these are not able to ensure degradation in natural environments. This is alarming, considering that a relevant parcel of plastic debris ends up in the oceans and reaches abyssal and hadal zones. Moreover, aquatic environments present ranges of microbial activity, pH, temperature, salinity, UV radiation and pressure that are not covered by any TS. Therefore, from a scientific perspective, claims of biodegradability placed on labels seeking to influence purchasing decisions can be considered an environmental rip off. Therefore, there is an urgent need to revise such TS, which must consider the real fate of plastic debris alongside microplastic formation and ecotoxicology effects. Furthermore, certification should provide information on time scale, degradation rates and, preferably, be globally harmonized.

Statement of novelty

While biodegradable polymers are recognized as strategy to minimize plastic pollution, standards used to attest biodegradability are not in compliance with environmental parameters in aquatic systems. These guidelines cover only a fraction of the biogeochemical parameters seen in nature largely disregarding deep-sea. Thus, they are not able to ensure degradation in natural conditions. Therefore, claims of biodegradability can be considered an environmental rip off. Was proposed a revision of such standards considering the fate of plastic alongside microplastic formation and ecotoxicology effects. Furthermore, the certification of bioplastics should provide information on time scale, degradation rates and be globally harmonized.

.

Graphical Abstract



Highlights

- Certification of biodegradability do not reflect degradation in natural environments.
- Ranges of biogeochemical factors observed on ocean are not covered by any guide.
- New biodegradability certification schemes should be globally adopted.
- Certification of biodegradable plastics must be tested under real ocean conditions.
- Microplastics formation should be monitored in degradation experiments.

Are biodegradable plastics an environmental rip off?

João S. C. Viera[a], Mônica R.C. Marques[b], Monick Cruz Nazareth[b], Paula Christine Jimenez[a], Carlos Sanz-Lazaro[c] and Ítalo Braga Castro[a*]

[a] Instituto do Mar, Universidade Federal de São Paulo (IMAR-UNIFESP), Rua Maria Máximo, 11030-100 Santos, SP, Brazil

[b] Programa de Pós-Graduação em Química do Instituto de Química, Universidade do Estado do Rio de Janeiro (UERJ), Rua São Francisco Xavier, 524 Pavilhão Haroldo Lisboa da Cunha, 20559-900, RJ, Brazil

[c] Department of Ecology, University of Alicante, PO Box 99, E-03080, Alicante, Spain

*Corresponding author: Ítalo Braga Castro - ibcastro@unifesp.br

Abstract

While the use of supposedly biodegradable polymers has been recognized as a global strategy to minimize plastic pollution, the technical standards (TS) used to attest biodegradability of alternative polymers may not be in compliance with most environmental parameters observed in marine and coastal ecosystems worldwide. Indeed, through a careful assessment of the TS currently in use, this study evidenced that these guidelines cover only a fraction of the diversity of biogeochemical parameters seen in nature and largely disregard the deep-sea. Thus, these are not able to ensure degradation in natural environments. This is alarming, considering that a relevant parcel of plastic debris ends up in the oceans and reaches abyssal and hadal zones. Moreover, aquatic environments present ranges of microbial activity, pH, temperature, salinity, UV radiation and pressure that are not covered by any TS. Therefore, from a scientific perspective, claims of biodegradability placed on labels seeking to influence purchasing decisions can be considered an environmental rip off. Therefore, there is an urgent need to revise such TS, which must consider the real fate of plastic debris alongside microplastic formation and ecotoxicology effects. Furthermore, certification should provide information on time scale, degradation rates and, preferably, be globally harmonized.

Keywords: bioplastic; technical standards; pollution; marine debris; contamination

Introduction

The occurrence of plastic debris in ocean and coastal areas has increased dramatically due to a growing demand for synthetic polymers and poor management after these polymers become residues. Studies indicate that in water surface of the North Central Pacific Gyre there are over 334,000 plastic fragments per square kilometer [1], while estimates point out 71.5 to 116 billion large (> 5mm) plastic debris on the ocean floor. It is worth mentioning that such values disregards microplastics, which are also widely distributed in sediments. In addition, up to 70% of plastic debris discarded in the oceans reaches the deep sea [2].

In this sense, the superficial fouling processes undergone by floating plastics may lead to sinking of such residues which reach benthic regions. In fact, plastic amounts in the seabed are several orders of magnitude higher than in the water column [3]. Further, plastic residues have been found beyond 1,000 km off the coast [4] and microplastics are abundant in the hadal sediments of the Marianas trench, ranging from 200 to 2,200 particles per liter [5]. After sedimentation, the plastic deposited on the ocean floor can still be resuspended and scattered by mechanical processes. According to Tosin et al., [6], evidences indicates that different types of plastics circulate through various marine and coastal environments due to oceanographic processes such as tides, currents and wind action. Many of these factors are also responsible for the transportation and global distribution of plastic debris. Therefore, along this cycle, plastic waste is exposed to a multitude of environmental conditions which influence their transformation processes [7,8].

Given the global issue of plastic pollution, scientific community and industry have proposed and adopted biodegradable materials as a strategy to replace traditional polymers Such materials, are supposedly able to be decomposed into CO_2 and water or

CH_4 by means of living organisms under a time frame comparable to average periods for disintegration of biological substances [9]. In addition, these materials were designed to suffer rapid degradation under environmental conditions. Simultaneously, technical standards (TS) have been developed to certify biodegradability properties of commercial products [10]. In fact, standardization can be critical in determining the success of emergent technologies and plays a vital role in supporting key technological trends, improving international trade and reducing costs and trade barriers [11]. Moreover, labels certifying that a product is biodegradable may positively influence buying decisions by consumers willing to pay extra for environmental benefits [12]. To meet certification purposes there are internationally recognized standardization bodies such as the International Standards Organization (ISO). Additionally, the American Society of Methods and Materials (ASTM), the European Standardization Committee (EN) and the Organization for Economic Cooperation and Development (OECD), operating at regional levels, increments the list. Furthermore, several other national institutions as French standardization association (AFNOR), have issued standards with protocols for certification of commercial plastic products. Although most of these certification bodies operate voluntarily with support of the industry, the TS produced often become part of the legal framework of governments, as in the European Union [13].

The TS used to analyze polymers biodegradability under controlled laboratory conditions often evaluate their conversion rates into carbon dioxide, water and biomass [14,15] considering a particular time frame. These TS establish minimum requirements, measure CO_2 emissions, or are based on visual evidence of degradation and loss of polymer mass [16]. During these experiments, polymer samples may be exposed to an artificially inoculated medium, which can be enriched with nutrients, and are kept under specific ranges of temperature and pH. Thus, the conditions are designed to assess biodegradability in optimal but artificial conditions, whereas the goal should be to simulate conditions of natural environments [17]. Considering the variety of natural environments experienced, seasonally and geographically, by plastic residues after irregular disposal, the degradation kinetics will depend on a complex combination of biotic and abiotic factors over which persists doubts if the tests established by TS are able ~~of reproduce~~ [18,19]. This situation is worrisome since, based on the obtained certifications, commercial products receive labels suggesting biodegradability under naturally existing conditions [10]. Based on these scenarios, the present study aimed to qualitatively assess whether the TS used to attest biodegradability of plastic polymers are in compliance with the majority of environmental parameters observed in marine and coastal ecosystems around the world.

Material and Methods

Several TS issued by different organizations to assess biodegradability of plastic polymers based on different parameters were chosen to quantify the degradation rates [20]. To carry out this study, TS for biodegradability of plastic products were obtained from the main publishing organizations in the world, as shown in Table 1. Subsequently, each standard was carefully reviewed and grouped according to the environment types for which the tests were designed (aqueous, soil and marine environments). The intervals of the physical-chemical parameters (temperature, pH, light incidence and inoculum) and the operational procedures including, exposure period and biodegradation rates described by each TS, were tabulated. Subsequently, the obtained data were compared to the biogeochemical parameters that mainly characterized marine and coastal environments of the world considering coastal and oceanic zones, as well deep-sea environments.

Results

A total of 17 TS issued by ASTM, ISO, EN, AFNOR and OECD were analyzed (Table 2). As far as we could verify, this set represents nearly all the technical guidelines developed worldwide to assess the biodegradability of plastic materials [10,21]. Considering the categories, were evaluated 4, 6 and 7 TS for soil, water and marine environments respectively.

Biodegradability of plastic polymers in soils

Soils present heterogeneous characteristics and their properties are affected by temperature, water content, chemical composition and pH. These parameters, separately or combined, create different conditions that exert a strong influence on polymer biodegradability [22,23]. Soils are usually where plastic waste is initially discarded [24]. In addition, soil covers made by plastic films has been globally employed as an efficient strategy to improve soil properties contributing to the growth of crops [25]. Thus, considering the impacts resulting from the use of conventional plastics, biodegradable polymer films have become ecological alternatives to polyethylene. Based on widespread use for agriculture purpose, specific standards for soil degradation of polymers have been developed, especially in the European Union [26]. Such actions, seeking to ban or reduce certain microplastics sources [27], are requiring certification of biodegradable plastic films for agriculture use [28].

The four TS directed at evaluating biodegradability of plastics in soil analyzed herein were designed to do so considering ideal and controlled conditions, and were issued by ASTM, CEN, AFINOR and ISO. These standards recommend exposure periods ranging from 2 weeks to 12 months, with temperatures between 20 and 37ºC, while soil pH conditions between 4.5 and 8 are also considered by AFNORNFU52-002 [29], ASTMD5247 [30], ASTMD5988 [31], ISO17556 [32]. The aerobic biodegradability rates considered acceptable by these standards are measured through oxygen demand or

CO_2 emissions and have been established in values between 60% and 90%, respectively. Considering the inoculum composition, only ASTMD5988 [33] and ISO17556 [34] recommend the use of forest and field soils. In addition, none of the documents mentions light exposure during the tests.

Biodegradability of plastic polymers in freshwater environments

High levels of microplastics have been reported for freshwater environments and estuaries. Nevertheless, specific biodegradability TS for plastic items deposited in open freshwater ecosystems have not been issued [18]. In contrast, several standards and experimental methods have been developed to measure the degree and rate of aerobic biodegradation of plastic materials in wastewater. The six TS analyzed that contemplate this matter, published by CEN and ISO, recommend exposure of plastic polymers to activated sludge from a sewage treatment plant and controlled digestion systems. Moreover, temperature ranges should be set between 20 and 58ºC and biodegradability rates must be measured by comparing biochemical to theoretical oxygen demands. TS issued by ISO [35,36] adopt experimental periods varying from 45 days to 6 months and specify the test should be performed under dark or diffused light conditions. All TS indicate pH values between 6 and 8.

Biodegradability of plastic polymers in marine environments

Seven TS, published by ASTM, ISO and OECD, describing methods for assessing biodegradability of plastic polymers were considered in this study. The ISO 18830 [37] and ISO19679 [38] TS assesses biodegradability for plastic materials in the water-sediment interface, simulating sublittoral-like conditions. On the other hand, ASTMD7991 [39] and ISO22404 [40] evaluate biodegradation considering conditions occurring in intertidal zones. ISO16221 [41] and OCDE306 [42] depict methods that weigh on biodegradability by aerobic microorganisms in static aqueous systems dissolving a determined amount of the material, incubated in the test medium. According to ASTMD6691 [43], aerobic biodegradation is assayed under laboratory conditions that simulate the pelagic zone by a defined microbial consortium, with the plastic sample suspended in a synthetic sea salt solution. In all cases, aerobic biodegradation is appraised by measurements of oxygen and CO_2 emissions under temperatures ranging from 15 to 30º C. Tests should span from 60 days up to 2 years, in which biodegradation rates must reach between 60 and 70%. In TS in which it is stated, pH should be adjusted within 7 and 8.5, while OECD306 [44] does not include this requirement.

Most of these TS imply the use of sediments and filtered seawater incorporating their natural microbiota; still this may be replaced by artificial seawater. In such cases, ASTMD6691 [43] specifies an inoculum containing a minimum of ten microorganisms including a defined taxa list. Additionally, samples of natural seawater must contain inorganic nutrients such as ammonium chloride and monopotassium phosphate and be obtained in uncontaminated areas. OECD306 [42] instructs the pretreatment of natural seawater to remove coarse particles and to add mineral nutrients such as nitrogen and phosphorus, however in concentrations higher than what are generally found in natural seawater. Likewise, salinity must be adjusted to 32 ppt according to OECD306 [42], ISO18830 [45] and ISO19679 [38], while ASTMD6691 [43] requires that to be 34 ppt. ISO22404 [40] and ISO16221 [41] and ASTMD7991 [39] do not specify salinity to run biodegradability tests.

Discussion

The TS issued by different institutions showed a lack of uniformity with physical and chemical properties observed in actual environments, which are known to influence biodegradation processes [46,47]. In Europe, the certification of biodegradability of materials created by Vinçotte and managed by TUV (OK Biodegradable) is the most broadly used and encompasses the following modalities: WATER, SOIL and MARINE. Regarding the MARINE modality, it has been based on the technical standard ASTM 6691, which measures the biodegradability of the material in the water column. However, oceans are composed by different environmental compartments (water column and seabed) resulting in dissimilar metabolic capacities to degrade materials. In this context, material degradation in the oceans, rather it is biodegradable plastic or algae, is mainly mediated by microorganisms. Sediments may shelter nearly 1,000 times more microorganisms than the water column [48], while various microbial groups known for their function as decomposers feed on organic matter and largely lodge in marine sediments [49]. Therefore, degradation processes occur in sediment at higher degrees than they do in the water column. Indeed, biodegradable plastics have been shown to have a 10 times greater degradation rate in the sediment than in the water column [7]. This is especially relevant given that 70% of plastic debris that reach the oceans end up in the sediment.

Physico-chemical parameters in oceans and coastal zones can vary dramatically in time and space. In this sense, studies have shown that pH, salinity, dissolved oxygen and temperature can differ substantially among samples collected within few centimeters or minutes apart [50,51]. Common oceanographic processes such as tides, currents, continental discharges and euryhaline circulation are crucial agents in such dynamics. Furthermore, storms, tsunami and other extreme events are also important factors to be considered when assessing the physico-chemical parameters of water and marine sediments [52]. Hence, fragments of biodegradable plastics discarded inappropriately will be subjected to a wide variety of biogeochemical conditions.

Temperature is a parameter that may present pronounced horizontal and vertical variations, as small oscillations in tidal cycles can induce changes in the order of 10°C over a single day. Sudden variations in temperature are also observed in coastal and oceanic areas where seasonal upwelling are typical, such as in South Africa, when these processes alter surface water temperatures, causing declines from 20°C to less than 17°C [53]. On the West Coast of North America, the recorded variations are of 3°C, reaching 9°C near the coasts of Oregon and California [54]. In addition, latitudinal variations in surface temperatures around 28ºC (in the equatorial zones) and -1.9ºC (at the poles) are often seen in Earth's oceans and seas [55].

Regarding ocean stratification, the warmest surface layers are separated from the deep cold ocean by thermoclines. Below these bands of abrupt variations – deep-sea regions represent 90% of oceanic areas, with a mean depth of 3,800m [56] –, the water column extends to the seafloor where the temperature averages 3.5ºC, while varying between 1ºC and 5ºC [57]. Under such perspective, temperature is a crucial factor in chemical reactions and may strongly influence metabolic activity of the microorganisms. In fact, a temperature rise of 10ºC can produce a two-fold increase in the metabolic capacity of the sediment [58]. Moreover, experiments carried out using Poly-3-hydroxybutyrate (P3HB) immersed in seawater, showed that at 27°C the biodegradation rates were almost twice as high as those observed in water at 10°C. Temperature influences biochemical reactions and taxonomic composition of microbial communities, controlling reproduction, growth and distribution of decomposing microorganisms, thus this is a key environmental parameter for biodegradability [59].

The examination conducted herein disclosed the temperatures adopted by some TS, like ASTM 6691 that requires experiments to be carried out at 30ºC, are generally far higher than the mean occurring temperature in the oceans. In this sense, considering the effects of this parameter on chemical reactions of any nature, the time allotted until full degradation of a material could significantly vary depending on the temperature selected.

In other cases, like in ISO 19679, temperature is not accurately specified, allowing ranges from 15 to 28ºC, which are excessively large and can result in marked dissimilarities in biodegradability outcomes, while being still very far from the conditions observed in the deep-sea. Furthermore, in the deep-sea, abiotic characteristics are mostly uniform, however hydrostatic pressure is a prevalent physical variable, which in the hadal systems can reach between 600 to 1100 atm. An environment enduring increased pressure along with reduced temperature is expected to impact the activity of enzymes in organisms therein [60]. Experiments using fungi isolated from the deep-sea revealed their reduced polymer degradation capacity under increased hydrostatic pressure, while no degradation could be observed above 296 atm [61].

Salinity is another environmental factor that affects polymer degradation rates as this further plays an essential role in the selection of microbial communities and over their metabolic activity [62]. In surface extracts from the oceans, salinity varies between 32 and 37 ups, with higher values found in semi-closed seas, where evaporation far exceeds precipitation, such as the Mediterranean Sea (37 to 39) and the Red Sea (40 to 41) [63]. On the other hand, runoff leads to salinity reduction (27 to 30) in coastal waters. In estuarine systems, salinity may vary between 0 and 30 [64], whereas in the deep ocean it tends to be more stable, averaging 34.8 [65]. Reasonably, only TS designed for marine environments recommend adjustments in this parameter (32 – 34), whereas those regarding non-saline circumstances, such as soil and freshwater environments, do not consider such parameter.

The pH in aquatic environments is fundamentally controlled by addition or removal of CO_2 due to physical and biological processes. This important parameter can be modified by up to one unit due to microbial activity and phytoplankton density. In addition, increases in partial pressure of CO_2 experienced after the industrial revolution have contributed to gradual decreases in the pH of global aquatic systems [66]. Especially in coastal areas, pH is subjected to daily and seasonal fluctuations. Thus, higher values are often observed during the summer owing to changes in water temperature and increased photosynthesis rates. Therefore, pH in coastal waters routinely vary between 7.5 and 8.5 [67], while lower values are usually observed in the eulittoral (5.5 to 6.8) and sublittoral (7.8 and 7.9). In contrast, in surface waters of open oceans, pH values are generally found between 7.9 and 8.3 [68]. In the deep ocean, vertical pH profiles reveal average values between 7.5 and 7.6 [68]. When confronted with the analyzed TS, pH values of 7, 6-8 and 7-8.5 are recommended for aqueous medium, soil and marine environments, respectively. Indeed, microorganisms from different groups are known to demand certain conditions to perform in degradation processes. For instance, fungi usually tolerate wider pH ranges compared to bacteria [69]. Studies carried out with butylene polyadipate-terephthalate (PBAT) and its biocomposites have shown this material to better degrade in activated sludge compound than in natural sea water (*in situ*). This study also showed that the low temperature and alkalinity of seawater stimulated the activity of psychrotrophic bacteria, while acidity in the sludge favored fungi activity [70]. On the counter side, polylactic acid (PLA), a known biodegradable polymer, underwent faster degradation in alkaline solutions influenced by the high concentration of hydroxide ions [71].

The penetration and distribution of light radiation in water bodies is dependent on depth and turbidity. In coastal regions, where the amount of particulate matter in suspension is high, the photic zone can vary from a few to 60 m depth. On the other hand, in pelagic environments, availability of light can reach 200m. Beyond this measure, dysphotic and aphotic zones show an evident decrease in incidence of light [72]. Therefore, the deepest portions of the ocean, which comprises 90% of its volume, remains in complete darkness. Degradation rates of plastic polymers are intensified in surface environments as photodegradation take up a significant share of the process [73,74]. Moreover, UV radiation also plays an essential role in the vertical distribution of microbial diversity [75]. In this regard, it is important to highlight that fungal and bacterial species produce enzymes that mediate biodegradation of bioplastics which are, directly or indirectly, dependent of light radiation [8,76]. Thus, light conditions should be a controlled variable in TS testing of biodegradability, and if darkness is not applied, light sources should be able to simulate the whole radiation spectrum that the oceans receive.

Although there are a wide variety of microorganisms and enzymes able to biodegrade polymers, these are not capable of universally degrading all types of plastics. Further, biodegradation rates are also dependent of polymer morphology and their physical and chemical properties. In this regard, the surface area, chemical structure, molecular mass, elasticity and crystalline structure are crucial features [77]. In addition, environmental parameters, such as humidity, temperature, pH, salinity and hydrostatic pressure, along with the availability and type of nutrients and presence of xenobiotics greatly influence the dynamics of microbial systems [78]. A recent study assessing degradation rates of polyhydroxybutyrate (PHB) and polybutylene sebacate-co-terephthalate (PBSeT) in three different marine environments showed sample disintegration under intertidal, pelagic and benthic conditions. However, significant differences in degradation rates were observed and related to the distinct abiotic and biotic conditions, which strongly influence microbiota diversity and function [79]. Another study, which evaluated degradation of polyhydroxyalkanoate (PHA) in marine environments under different climatic zones, showed disintegration rates related to light exposure, temperature and oxygen [80]. Therefore, considering that microbiota is connected to habitat [81], formulated inoculums are unlikely to approximate accurate microbial consortia of marine environments. In this regard, ASTMD6691 [82] indorses the use of either local sea water for an inoculum or one consisting of a minimum of ten organisms, then listing the following species, claiming to have been identified by Gram staining and biochemical evidences: *Alteromonas haloplanktis*, *Xanthomonas campestri*, *Vibrio alginolyticus*, *Vibrio proteolyticus*, *Actinomycete* sp., *Bacillus megaterium*, *Bacillus* sp., *Zooster* sp. and *Pseudomonas* sp. It must be noted, herein, that this list is constant since, at least, the 2009 version of this document, which seemingly reflects the bacteria identified in a certain environmental sample used to run the modeled experiment, and not a reproduceable consortium of microorganisms which would, thus, allow standardization of this protocol. Moreover, to the best our knowledge, *Zooster* sp. and *Actinomycete* sp. are not valid microorganism taxa. In such a scenario, one cannot overlook the title held by the ASTMD6691 [82] (*Standard test method for determining aerobic biodegradation of plastic materials in the marine environment by a defined microbial consortium or natural sea water inoculum*), for which the guidelines provide fragile, under sought and inconsistent instructions on how to certify for biodegradability in the marine environment.

Analogously, the tests provided by ASTM D5247- 92, which employ soil-specific microorganisms, limit the plastic samples as the only carbon source, although, in natural environments, the tested polymer may not be the preferred substrate in the presence of more conventional nutrients. Furthermore, the ISO 16221-01, ASTM D6691-17 and OECD 306-92, which add mineral nutrients to the inoculum, can stimulate growth and microbial activity in a different way than what in fact occurs in natural environments, while studies have indicated that nutrient addiction affects the degradation process (Tosin et al., 2012b). Furthermore, the microorganisms used in experimental conditions generally differ quantitatively and qualitatively from the environmental microbiota [83].

On the other hand, as it is reasonable to agree that achieving an environmentally accurate microbial inoculum to be used under experimental conditions is not feasible, the means by which TS access and ponder microorganisms in degradation processes is still far from allowing their adequate use in certification schemes.

Biodegradable plastics may contain toxic substances that can be released during the degradation process [84]. Thus, TS should include assessments of the potential toxicity derived from the biodegradation process of the tested materials. In this regard, TUV's OK Biodegradable, based on ASTMD6691 [82] includes a standard for ecotoxicity tests using *Daphnia sp*. [85]. The certification scheme from the US Environmental Protection Agency also indicates further protocols for ecotoxicity assessments using other organisms, such as fish, algae and cyanobacteria, but does not clarify if these tests must be performed in order to certify the materials. Moreover, the toxicity induced during biodegradation process, could also be related to formation of microplastics, which are becoming of substantial concern since those could be the most harmful portion of plastics debris. Due to their reduced size (< 5 mm), these materials can be ingested and prompt immune and neurotoxicity disorders [86]. Moreover, microplastic also act as carriers for other pollutants and/or additives adsorbed to their surface, which can then become bioavailable during degradation [87]. In this sense, there is no technical standard for certification of biodegradability of plastic polymers that considers microplastic formation as an intermediate or end product.

Final remarks

Biodegradability is a widely misused term that has been distorted generally aiming to give a specific product an added "green" value that, in many cases, is not accurate. At least in part, this issue is derived from the lack consensus on biodegradability meaning. Indeed, decomposition under natural conditions may present different time frames depending on the specific environmental variables. Thus, a biodegradability concept must always be linked to a specific environment [9]. Biologically diverse marine environments cover about 70% of the Earth's surface [88], offering 300 times more habitable space than terrestrial and freshwater environments. In addition, these areas portray a remarkable diversity of physical and chemical conditions [64]. The TS currently in use contemplate only a fraction of this diversity and largely disregard the deep-sea, where 32% of the accumulated debris are plastic, most of which (89%) are from single-use utensils [4]. These environments have specific ranges of microbial activity, pH, temperature, salinity and pressure that are not fully covered by any technical standard. Even the TS designed to simulate marine environments have established experimental conditions that are far from real environmental parameters.

Despite this, labels claiming biodegradability of these materials are currently issued based on tests carried out using TS which do not reflect their degradation in natural environments. As such labels wield a positive influence on consumers' purchasing decision, they certainly portray an environmental rip off. Therefore, ideal TS for attesting degradation should consider deep-sea environmental conditions, which could provide a more appropriate assessment on material biodegradability for these ecosystems. Considering the above, we propose three key points that new biodegradability certification schemes should consider: (1) simulation of deep-sea environmental conditions as much as possible, taking into consideration temperatures close to 0ºC and absence of light, among other factors; (2) using toxicity tests to assess potential toxicity through degradation and (3) monitoring of microplastic formation. Furthermore, it is important that new TS make truly clear to the users the meaning of the certification, providing information on time scale and degradation rates. Finally, as plastic waste is subject to uncontrollable cross-border movements, worldwide harmony among certification schemes is a real necessity in a globalized and interconnected planet.

Acknowledgments:

This research was support by São Paulo Research Foundation (FAPESP n. 2019/13750-4). I.B. Castro (PQ 302713/2018-2) and M.R.C. Marques (PQ 304295/2018-3) were recipient of research productivity fellowship from the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq). M.C. Nazareth was sponsored by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES / Finance code: 001).

Table Captions

Table 1: Technical standards currently used to assess the biodegradability of plastic polymers.

Table 2: Main parameters used to assess biodegradability of plastic materials according to several technical standards.

References

[1] W.C. Li, H.F. Tse, L. Fok, Plastic waste in the marine environment: A review of sources, occurrence and effects, Science of The Total Environment. 566–567 (2016) 333–349. https://doi.org/10.1016/j.scitotenv.2016.05.084.

[2] F. Galgani, G. Hanke, T. Maes, Global Distribution, Composition and Abundance of Marine Litter, in: M. Bergmann, L. Gutow, M. Klages (Eds.), Marine Anthropogenic Litter, Springer International Publishing, Cham, 2015: pp. 29–56. https://doi.org/10.1007/978-3-319-16510-3_2.

[3] G. Erni-Cassola, V. Zadjelovic, M.I. Gibson, J.A. Christie-Oleza, Distribution of plastic polymer types in the marine environment; A meta-analysis, Journal of Hazardous Materials. 369 (2019) 691–698. https://doi.org/10.1016/j.jhazmat.2019.02.067.

[4] S. Chiba, H. Saito, R. Fletcher, T. Yogi, M. Kayo, S. Miyagi, M. Ogido, K. Fujikura, Human footprint in the abyss: 30 year records of deep-sea plastic debris, Marine Policy. 96 (2018) 204–212. https://doi.org/10.1016/j.marpol.2018.03.022.

[5] X. Peng, M. Chen, S. Chen, S. Dasgupta, H. Xu, K. Ta, M. Du, J. Li, Z. Guo, S. Bai, Microplastics contaminate the deepest part of the world's ocean, Geochemical Perspectives Letters. 9 (2018) 1–5. https://doi.org/10.7185/geochemlet.1829.

[6] M. Tosin, M. Weber, M. Siotto, C. Lott, F. Degli-Innocenti, Laboratory Test Methods to Determine the Degradation of Plastics in Marine Environmental Conditions, Frontiers in Microbiology. 3 (2012) 225. https://doi.org/10.3389/fmicb.2012.00225.

[7] A. Beltrán-Sanahuja, N. Casado-Coy, L. Simó-Cabrera, C. Sanz-Lázaro, Monitoring polymer degradation under different conditions in the marine environment, Environmental Pollution. 259 (2020) 113836. https://doi.org/10.1016/j.envpol.2019.113836.
[8] S.M. Emadian, T.T. Onay, B. Demirel, Biodegradation of bioplastics in natural environments, Waste Management. 59 (2017) 526–536. https://doi.org/10.1016/j.wasman.2016.10.006.
[9] A.-C. Albertsson, M. Hakkarainen, Designed to degrade, Science. 358 (2017) 872. https://doi.org/10.1126/science.aap8115.
[10] J.C. Philp, A. Bartsev, R.J. Ritchie, M.-A. Baucher, K. Guy, Bioplastics science from a policy vantage point, New Biotechnology. 30 (2013) 635–646.
[11] P.M. Wiegmann, H.J. de Vries, K. Blind, Multi-mode standardisation: A critical review and a research agenda, Research Policy. 46 (2017) 1370–1386. https://doi.org/10.1016/j.respol.2017.06.002.
[12] J.S.C. Viera, M.R.C. Marques, M.C. Nazareth, P.C. Jimenez, Í.B. Castro, On replacing single-use plastic with so-called biodegradable ones: The case with straws, Environmental Science & Policy. 106 (2020) 177–181. https://doi.org/10.1016/j.envsci.2020.02.007.
[13] UNE, Report on the standardization landscape and applicable standards, 2017. https://circpack.eu/fileadmin/user_upload/DLV7.4_Standardization_map_UNE_VF.pdf.
[14] EN 13432, Requisitos para embalagens recuperáveis através de compostagem e biodegradação – esquema de teste e critérios de avaliação para aceitação final da embalagem., 2000.
[15] EN 14046, Embalagem – avaliação da biodegradabilidade aeróbica final dos materiais de embalagem sob condições controladas de compostagem – método por análise de dióxido de carbono liberado., 2003.
[16] S. Chinaglia, M. Tosin, F. Degli-Innocenti, Biodegradation rate of biodegradable plastics at molecular level, Polymer Degradation and Stability. 147 (2018) 237–244.
[17] A. Krzan, S. Hemjinda, S. Miertus, A. Corti, E. Chiellini, Standardization and certification in the area of environmentally degradable plastics, Polymer Degradation and Stability. 91 (2006) 2819–2833. https://doi.org/10.1016/j.polymdegradstab.2006.04.034.
[18] J.P. Harrison, C. Boardman, K. O'Callaghan, A.-M. Delort, J. Song, Biodegradability standards for carrier bags and plastic films in aquatic environments: a critical review, Royal Society Open Science. 5 (2018) 171792.
[19] B. Laycock, M. Nikolić, J.M. Colwell, E. Gauthier, P. Halley, S. Bottle, G. George, Lifetime prediction of biodegradable polymers, Progress in Polymer Science. 71 (2017) 144–189. https://doi.org/10.1016/j.progpolymsci.2017.02.004.
[20] R. Jayasekara, I. Harding, I. Bowater, G. Lonergan, Biodegradability of a selected range of polymers and polymer blends and standard methods for assessment of biodegradation, Journal of Polymers and the Environment. 13 (2005) 231–251.
[21] A. Ammala, S. Bateman, K. Dean, E. Petinakis, P. Sangwan, S. Wong, Q. Yuan, L. Yu, C. Patrick, K.H. Leong, An overview of degradable and biodegradable polyolefins, Prog. Polym. Sci. 36 (2011) 1015.
[22] A. Hoshino, H. Sawada, M. Yokota, M. Tsuji, K. Fukuda, M. Kimura, Influence of weather conditions and soil properties on degradation of biodegradable plastics in soil, Soil Science and Plant Nutrition. 47 (2001) 35–43. https://doi.org/10.1080/00380768.2001.10408366.

[23] F. Maréchal, Biodegradable Plastics, in: E. Chiellini, R. Solaro (Eds.), Biodegradable Polymers and Plastics, Springer US, Boston, MA, 2003: pp. 67–71.
[24] Y. Chae, Y.-J. An, Current research trends on plastic pollution and ecological impacts on the soil ecosystem: A review, Environmental Pollution. 240 (2018) 387–395.
[25] X. Zhang, S. You, Y. Tian, J. Li, Comparison of plastic film, biodegradable paper and bio-based film mulching for summer tomato production: Soil properties, plant growth, fruit yield and fruit quality, Scientia Horticulturae. 249 (2019) 38–48. https://doi.org/10.1016/j.scienta.2019.01.037.
[26] F. Touchaleaume, L. Martin-Closas, H. Angellier-Coussy, A. Chevillard, G. Cesar, N. Gontard, E. Gastaldi, Performance and environmental impact of biodegradable polymers as agricultural mulching films, Chemosphere. 144 (2016) 433–439. https://doi.org/10.1016/j.chemosphere.2015.09.006.
[27] J. Šerá, L. Serbruyns, B. De Wilde, M. Koutný, Accelerated biodegradation testing of slowly degradable polyesters in soil, Polymer Degradation and Stability. 171 (2020) 109031. https://doi.org/10.1016/j.polymdegradstab.2019.109031.
[28] EN 17033, Plastics - Biodegradable mulch films for use in agriculture and horticulture - Requirements and test methods, 2018.
[29] AFNOR NF U52-001, Materiais biodegradáveis., (2005).
[30] ASTM D5247, Método de teste padrão para determinação da biodegradabilidade aeróbica de plásticos degradáveis por microrganismos específicos ., 1992.
[31] ASTM D5988, Método de teste-padrão para determinar a biodegradação aeróbica no solo de materiais plásticos ou material plástico residual após a compostagem., 2018.
[32] ISO 17556, Pláticos – determinação do grau de desintegração de materiais sob condições de compostagem em um teste de escala piloto., 2019.
[33] ASTM D5988-18, Test Method for Determining Aerobic Biodegradation of Plastic Materials in Soil, ASTM International, 2018. https://doi.org/10.1520/D5988-18.
[34] ISO 17556, Plastics — Determination of the ultimate aerobic biodegradability of plastic materials in soil by measuring the oxygen demand in a respirometer or the amount of carbon dioxide evolved, ISO. (2019). https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/07/49/74993.html (accessed November 17, 2020).
[35] ISO 14851, Determinação da biodegradabilidade aeróbica final de materiais plásticos em meio aquoso – método através da medição da demanda de oxigênio em um respirômetro fechado, 2019.
[36] ISO 14852, Determinação da biodegradabilidade aeróbia final de materiais plásticos em meio aquoso – método por análise de dióxido de carbono., 2018.
[37] ISO18830, Determinação da biodegradação aeróbica de materiais plásticos não flutuantes em uma interface água do mar / sedimentos arenosos - Método através da medição da demanda de oxigênio no respirômetro fechado, 2016.
[38] ISO19679, Determinação da biodegradação aeróbica de materiais plásticos não flutuantes em uma interface água do mar / sedimentos - Método por análise de dióxido de carbono evoluído., 2020.
[39] ASTMD7991, Método de teste padrão para determinação da biodegradação aeróbica de plásticos enterrados em sedimentos marinhos arenosos em condições laboratoriais controladas, 2015.
[40] ISO 22404, Plásticos - Determinação da biodegradação aeróbica de materiais não flutuantes expostos a sedimentos marinhos., 2019.
[41] ISO 16221, Qualidade da água – orientação para determinação da

biodegradabilidade no ambiente marinho., 2001.
[42] OCDE 306, Biodegradabilidade em água do mar., 1992.
[43] ASTM D6691, Método de Teste Padrão para Determinação da Biodegradação Aeróbica de Materiais Plásticos no Ambiente Marinho por um Consórcio Microbiano Definido ou Inóculo Natural de Água do Mar., 2017.
[44] OECD, 306, OECD Guideline for Testing of Chemicals (306): Biodegradability in Seawater, n.d. https://www.oecd-ilibrary.org/environment/test-no-306-biodegradability-in-seawater_9789264070486-en.
[45] ISO18830, Determinação da biodegradação aeróbica de materiais plásticos não flutuantes em uma interface água do mar / sedimentos arenosos - Método através da medição da demanda de oxigênio no respirômetro fechado., 2016.
[46] E. Balestri, V. Menicagli, F. Vallerini, C. Lardicci, Biodegradable plastic bags on the seafloor: A future threat for seagrass meadows?, Science of The Total Environment. 605–606 (2017) 755–763. https://doi.org/10.1016/j.scitotenv.2017.06.249.
[47] J.-M. Restrepo-Flórez, A. Bassi, M.R. Thompson, Microbial degradation and deterioration of polyethylene – A review, International Biodeterioration & Biodegradation. 88 (2014) 83–90. https://doi.org/10.1016/j.ibiod.2013.12.014.
[48] B.C. Sander, J. Kalff, Factors controlling bacterial production in marine and freshwater sediments, Microbial Ecology. 26 (1993) 79–99. https://doi.org/10.1007/BF00177045.
[49] X. Luo, X. Xiang, G. Huang, X. Song, P. Wang, K. Fu, Bacterial Abundance and Physicochemical Characteristics of Water and Sediment Associated with Hydroelectric Dam on the Lancang River China, International Journal of Environmental Research and Public Health. 16 (2019) 2031. https://doi.org/10.3390/ijerph16112031.
[50] C.A. Frieder, S.H. Nam, T.R. Martz, L.A. Levin, High temporal and spatial variability of dissolved oxygen and pH in a nearshore California kelp forest., Biogeosciences. 9 (2012).
[51] O. Guadayol, N.J. Silbiger, M.J. Donahue, F.I. Thomas, Patterns in temporal variability of temperature, oxygen and pH along an environmental gradient in a coral reef, PloS One. 9 (2014) e85213.
[52] Í.B. Castro, Improper environmental sampling design bias assessments of coastal contamination, Trends in Environmental Analytical Chemistry. 24 (2019) e00068.
[53] J.R.E. Lutjeharms, J.M. Meeuwis, The extent and variability of South-East Atlantic upwelling, South African Journal of Marine Science. 5 (1987) 51–62. https://doi.org/10.2989/025776187784522621.
[54] G. Rehder, R.W. Collier, K. Heeschen, P.M. Kosro, J. Barth, E. Suess, Enhanced marine CH4 emissions to the atmosphere off Oregon caused by coastal upwelling, Global Biogeochemical Cycles. 16 (2002) 2–1. https://doi.org/10.1029/2000GB001391.
[55] Open-Bio, Work Pachage 5 In situ, biodegradation deliverable review of curret methods and standards relevant to marine degradation, 2015. www.OpenUBio.eu (accessed July 17, 2019).
[56] E. Ramirez-Llodra, A. Brandt, R. Danovaro, B. De Mol, E. Escobar, C.R. German, L.A. Levin, P. Martinez Arbizu, L. Menot, P. Buhl-Mortensen, B.E. Narayanaswamy, C.R. Smith, D.P. Tittensor, P.A. Tyler, A. Vanreusel, M. Vecchione, Deep, diverse and definitely different: unique attributes of the world's largest ecosystem, Biogeosciences. 7 (2010) 2851–2899. https://doi.org/10.5194/bg-7-2851-2010.

[57] R. Chester, T. Jickells, Descriptive oceanography: water -column parameters., in: Marine Geochemistry, John Wiley & Sons, Ltd, Chichester, UK, 2012: pp. 125–153. https://doi.org/10.1002/9781118349083.ch7.
[58] C. Sanz-Lázaro, T. Valdemarsen, A. Marin, M. Holmer, Effect of temperature on biogeochemistry of marine organic□enriched systems: Implications in a global warming scenario, Ecological Applications. 21 (2011) 2664–2677.
[59] A. Pischedda, M. Tosin, F. Degli-Innocenti, Biodegradation of plastics in soil: The effect of temperature, Polymer Degradation and Stability. 170 (2019) 109017. https://doi.org/10.1016/j.polymdegradstab.2019.109017.
[60] J.D. Gage, P.A. Tyker, The physical environment of the deep-sea, in: Deep-Sea Biology: A Natural Histoy of Organisms at the Deep-Sea Floor, Cambridge University Press, 1991: p. 18 a 28.
[61] K.E. Gonda, D. Jendrossek, H.P. Molitoris, Fungal degradation of the thermoplastic polymer poly-ß-hydroxybutyric acid (PHB) under simulated deep sea pressure, in: G. Liebezeit, S. Dittmann, I. Kröncke (Eds.), Life at Interfaces and Under Extreme Conditions, Springer Netherlands, Dordrecht, 2000: pp. 173–183.
[62] T. Artham, M. Doble, Biodegradation of Aliphatic and Aromatic Polycarbonates, Macromolecular Bioscience. 8 (2008) 14–24. https://doi.org/10.1002/mabi.200700106.
[63] P.C. Fiedler, Ocean Environments, in: B. Würsig, J.G.M. Thewissen, K.M. Kovacs (Eds.), Encyclopedia of Marine Mammals (Third Edition), Academic Press, 2018: pp. 649–654. https://doi.org/10.1016/B978-0-12-804327-1.00014-5.
[64] C.M. Lalli, T.R. Parsons, Biological Oceanography: An Introduction, The open university, 1997.
[65] F.J. Millero, Chemical Oceanography, 4th ed., Taylor & Francis Group, 2016.
[66] B. Hönisch, A. Ridgwell, D.N. Schmidt, E. Thomas, S.J. Gibbs, A. Sluijs, R. Zeebe, L. Kump, R.C. Martindale, S.E. Greene, W. Kiessling, J. Ries, J.C. Zachos, D.L. Royer, S. Barker, T.M. Marchitto, R. Moyer, C. Pelejero, P. Ziveri, G.L. Foster, B. Williams, The Geological Record of Ocean Acidification, Science. 335 (2012) 1058. https://doi.org/10.1126/science.1208277.
[67] P. Kerrison, J.M. Hall-Spencer, D.J. Suggett, L.J. Hepburn, M. Steinke, Assessment of pH variability at a coastal CO2 vent for ocean acidification studies, Estuarine, Coastal and Shelf Science. 94 (2011) 129–137. https://doi.org/10.1016/j.ecss.2011.05.025.
[68] A.G. Dickson, The measurement of sea water pH, Marine Chemistry. 44 (1993) 131–142. https://doi.org/10.1016/0304-4203(93)90198-W.
[69] H.-C. Flemming, Relevance of biofilms for the biodeterioration of surfaces of polymeric materials*, Polymer Degradation and Stability. 59 (1998) 309–315. https://doi.org/10.1016/S0141-3910(97)00189-4.
[70] K. Krasowska, J. Brzeska, M. Rutkowska, H. Janik, M.S. Sreekala, K. Goda, S. Thomas, Environmental degradation of ramie fibre reinforcedbiocomposites., Polish Journal of Environmental Studies. (2010) 937–945.
[71] M. Karamanlioglu, R. Preziosi, G.D. Robson, Abiotic and biotic environmental degradation of the bioplastic polymer poly(lactic acid): A review, Polymer Degradation and Stability. 137 (2017) 122–130. https://doi.org/10.1016/j.polymdegradstab.2017.01.009.
[72] A. Mitra, S. Zaman, Basics of Marine and Estuarine Ecology, Springer New York, índia, 2016.
[73] M. Bergmann, L. Gutow, M. Klages, Marine anthropogenic litter, Springer, 2015.

[74] N.F.A. Biber, A. Foggo, R.C. Thompson, Characterising the deterioration of different plastics in air and seawater, Marine Pollution Bulletin. 141 (2019) 595–602. https://doi.org/10.1016/j.marpolbul.2019.02.068.
[75] V.I. Rich, R.M. Maier, Chapter 6 - Aquatic Environments, in: I.L. Pepper, C.P. Gerba, T.J. Gentry (Eds.), Environmental Microbiology (Third Edition), Academic Press, San Diego, 2015: pp. 111–138. https://doi.org/10.1016/B978-0-12-394626-3.00006-5.
[76] J. Jacquin, J. Cheng, C. Odobel, C. Pandin, P. Conan, M. Pujo-Pay, V. Barbe, A.-L. Meistertzheim, J.-F. Ghiglione, Microbial Ecotoxicology of Marine Plastic Debris: A Review on Colonization and Biodegradation by the "Plastisphere," Frontiers in Microbiology. 10 (2019) 865. https://doi.org/10.3389/fmicb.2019.00865.
[77] Y. Tokiwa, P.B. Calabia, U.C. Ugwu, S. Aiba, Biodegradability of Plastics, International Journal of Molecular Sciences. 10 (2009). https://doi.org/10.3390/ijms10093722.
[78] S.K. Kale, A.G. Deshmukh, M.S. Dudhare, V.B. Patil, Microbial degradation of plastic: a review, Journal of Biochemical Technology. 6 (2015) 952–961.
[79] D. Briassoulis, A. Pikasi, Chr. Briassoulis, A. Mistriotis, Disintegration behaviour of bio-based plastics in coastal zone marine environments: A field experiment under natural conditions, Science of The Total Environment. 688 (2019) 208–223. https://doi.org/10.1016/j.scitotenv.2019.06.129.
[80] C. Lott, A. Eich, B. Unger, D. Makarow, G. Battagliarin, K. Schlegel, M.T. Lasut, M. Weber, Field and mesocosm methods to test biodegradable plastic film under marine conditions, BioRxiv. (2020) 2020.01.31.928606. https://doi.org/10.1101/2020.01.31.928606.
[81] J. Li, W. Huang, R. Jiang, X. Han, D. Zhang, C. Zhang, Are bacterial communities associated with microplastics influenced by marine habitats?, Science of The Total Environment. 733 (2020) 139400. https://doi.org/10.1016/j.scitotenv.2020.139400.
[82] ASTMD6691, Método de Teste Padrão para Determinação da Biodegradação Aeróbica de Materiais Plásticos no Ambiente Marinho por um Consórcio Microbiano Definido ou Inóculo Natural de Água do Mar, 2017.
[83] T.P. Haider, C. Völker, J. Kramm, K. Landfester, F.R. Wurm, Plastics of the Future? The Impact of Biodegradable Polymers on the Environment and on Society, Angewandte Chemie International Edition. 58 (2019) 50–62. https://doi.org/10.1002/anie.201805766.
[84] F. Degli-Innocenti, G. Bellia, M. Tosin, A. Kapanen, M. Itävaara, Detection of toxicity released by biodegradable plastics after composting in activated vermiculite, Polymer Degradation and Stability. 73 (2001) 101–106. https://doi.org/10.1016/S0141-3910(01)00075-1.
[85] OECD 202, Daphnia sp. Acute Immobilisation Test, 2004.
[86] H. Ma, S. Pu, S. Liu, Y. Bai, S. Mandal, B. Xing, Microplastics in aquatic environments: Toxicity to trigger ecological consequences, Environmental Pollution. 261 (2020) 114089. https://doi.org/10.1016/j.envpol.2020.114089.
[87] M. Smith, D.C. Love, C.M. Rochman, R.A. Neff, Microplastics in Seafood and the Implications for Human Health, Current Environmental Health Reports. 5 (2018) 375–386. https://doi.org/10.1007/s40572-018-0206-z.
[88] A.M.P. Walag, Bioactivities of extracts from different marine organisms around the world (2000 to present), Clin Oncol. 2 (2017) 355–361.

Table 1: Technical standards currently used to assess the biodegradability of plastic polymers.

Standard	Description
ASTM D5511-2018	Standard test method for determining anaerobic biodegradation of plastic materials under high-solids anaerobic-digestion conditions
ASTM D5988-2003	Standard test method for determining aerobic biodegradation of plastic materials in soil
ASTM D6691-2017	Standard test method for determining aerobic biodegradation of plastic materi the marine environment by a defined microbial consortium or natural sea inoculum
ASTM D7991-2015	Standard test method for determining aerobic biodegradation of plastics buried in sandy marine sediment under controlled laboratory conditions
EN 14047:2002	Packaging. Determination of the ultimate aerobic biodegradability of packaging materials in an aqueous medium. Method by analysis of evolved carbon dioxide
EN 14048:2002	Packaging. Determination of the ultimate aerobic biodegradability of packaging materials in an aqueous medium. Method by measuring the oxygen demand in a closed respirometer
EN 17033:2018	Plastics. Biodegradable mulch films for use in agriculture and horticulture. Requirements and test methods
ISO 13975:2019	Plastics — Determination of the ultimate anaerobic biodegradation of plastic materials in controlled slurry digestion systems — Method by measurement of biogas production
ISO 14851:1999	Determination of the ultimate aerobic biodegradability of plastic materials in an aqueous medium — Method by measuring the oxygen demand in a closed respirometer
ISO 14852:2018	Determination of the ultimate aerobic biodegradability of plastic materials in an aqueous medium — Method by analysis of evolved carbon dioxide — Technical Corrigendum
ISO 14853:2016	Plastics — Determination of the ultimate anaerobic biodegradation of plastic materials in an aqueous system — Method by measurement of biogas production
ISO 17556:2003	Plastics — Determination of the ultimate aerobic biodegradability in soil by measuring the oxygen demand in a respirometer or the amount of carbon dioxide evolved
ISO 16221:2001	Water quality — Guidance for determination of biodegradability in the marine environment
ISO18830: 2016	Plastics — Determination of aerobic biodegradation of non-floating plastic materials in a seawater/sandy sediment interface — Method by measuring the oxygen demand in closed respirometer
ISO19679: 2020	Plastics — Determination of aerobic biodegradation of non-floating plastic materials in a seawater/sediment interface — Method by analysis of evolved carbon dioxide
ISO 22404:2019	Plastics — Determination of the aerobic biodegradation of non-floating materials exposed to marine sediment — Method by analysis of evolved carbon dioxide
AFNOR NF U52-001	Biodegradable materials for use in agriculture and horticulture - Mulching products - Requirements and test methods
OCDE 306	Biodegradability in Seawater

Table 2: Main parameters used to assess biodegradability of plastic materials according to several technical standards.

Medium	Certification body	Technical Standard	pH	Exposure time	Inoculum	Measurements	Temperature	% Biodegradation
Soil	ASTM	D5988-18	4.5 - 8	2 weeks to - 4months	Bacteria / fungi / soil	CO_2 emission, mass loss, tensile strength	20 - 37ºC	70%
	ISO	17556:03	6 - 8	6 - 24 months	Field or forest soil	O_2 uptake and CO_2 emissions	20 - 28ºC	60%
	AFNOR	NF U52-001	6 - 8	12 months	N/C	CO_2 emissions	28ºC	60%
	EN	17033-12	N/C	24 months	Field or forest soil	CO_2 emissions	20–28 ° C	90%
Aqueous	EN	14047:02 14048:02	7.7	45 - 55 days	Minerals	O_2 uptake and CO_2 emissions	20 - 58ºC	70%
	ISO	14851-99 14852-99 13975-12 14853-16	6 - 8	3 - 6 months	Soil / sludge / compost	ratio between biochemical oxygen demand and theoretical oxygen demand	20 - 25º C	60 a 70%
Seawater	ASTM	D6691-17 D7991-15	7 - 8	3 months to 2 years	Sediments / seawater	CO conversion to CO_2	15 - 30ºC	60 a 70%
	ISO	18830:16 19679:01 16221:01 22404:19	7 – 8.5	60 days to 24 months	Sediments / seawater	O_2 uptake and CO_2 emissions	15–28º C	60 a 70%
	OCDE	306:92	N/C	60 days	Treated seawater	Chemical oxygen demand	15-20°C	> 60%